Working Paper

THE EFFECT OF CLIMATIC VARIATIONS ON AGRICULTURAL RISK

M.L. Parry
T.R. Carter

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WP-84-69

International Institute for Applied Systems Analysis
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FOREWORD

Over the past decade the international scientific community and even the popular media have been paying increasing attention to long-range climate change--the extent and timing of global warming, shifts in precipitation patterns, ecological, economic, and even geo-political effects.

Considerable research attention should obviously be addressed to the prospects for and implications of seminal climate change; such a development could have historic consequences. But the global scale and the long-term nature of the challenge, together with the uncertainties still to be resolved, tend to make the CO_2/climate issue, as it is usually presented, a residual claimant for the time and attention of national and international policy communities. This working paper, *The Effect of Climatic Variations on Agricultural Risk*, approaches the problem of climate change from a different perspective in terms of both spatial and temporal scales. It addresses "present day impacts from short-term climate variability". And it examines, as a case in point, the shifts of climate-related risk level and agricultural growth potential for a single crop (oats) in a single locality (southern Scotland).

But, however interesting this may be as an exercise in analyzing the climate-risk issue under a particular set of conditions in a particular area, the authors have a larger objective in mind: they wish to use their investigation of change of risk as a building block for assessing the consequences for agriculture of long-term (CO_2-induced) climate change. Such an approach, I believe, will provide useful guidance for those contemporary officials for whom a relatively remote, world-wide shift on temperature and precipitation is too emphemeral to appear on already-crowded policy agendas.

Professor Martin Parry and his associates at IIASA are investigating the impacts of short-term climatic variations and the likely long-term effects of CO_2-induced climatic changes on food output at the sensitive margins of production. This work is part of a two-year effort and is expected to be completed by December, 1985.

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ABSTRACT

The thesis of this paper is that impacts from climatic change can be evaluated effectively as changes in the frequency of short-term, anomalous climatic events. These can then be expressed as changes in the level of risk of impact from climatic extremes. To evaluate this approach, the risk of crop failure resulting from low levels of accumulated temperature is assessed for oats farming in southern Scotland. Annual accumulated temperatures are calculated for the 323-year long temperature record compiled by Manley for Central England. These are bridged across to southern Scotland and, by calculating mean levels of risk for different elevations, an average "risk surface" is constructed. 1-in-10 and 1-in-50 frequencies of crop failure are assumed to delineate a high-risk zone, which is mapped for the 323-year period by constructing isopleths of these risk levels. By re-drawing the risk isopleths for warm and cool 50-year periods, the geographical shift of the high-risk zone is delineated. The conclusion is that relatively recent and apparently minor climatic variations in the United Kingdom have in fact induced substantial spatial changes in levels of agricultural risk. An advantage of expressing climatic change as a change in agricultural risk, is that support programs for agriculture can be re-tuned to accommodate acceptable frequencies of impact by adjusting support levels to match new risk levels.

CONTENTS

THE EFFECT OF CLIMATIC VARIATIONS ON AGRICULTURAL RISK

M.L. Parry and T.R. Carter

1. Introduction

In the field of climate impact assessment there has been a tendency to distinguish between the role of short-term climatic variability and the role of long-term climatic change. One affects the range and frequency of shocks that society absorbs or to which it adjusts. The other alters the resource base, for example the agro-climatic resources that can affect farming options and the patterns of comparative advantage, which themselves help to determine why some crops are grown in one place and different crops in another. Following this line of thought, some studies have attended specifically to those shifts of cropping zones that might occur as a result of long-term changes in mean climate (Williams and Oakes, 1978; Newman, 1980).

Yet this distinction between short-term and long-term reflects more statistical convenience than an understanding of human behavior. Few societies or individuals look far ahead or behind. Farmers, for example, may plan over one or two years but rarely more than five. Any *future* impact from long-term changes in mean climate can thus be seen as being embedded in *present-day* impacts from short-term climatic variability; and it is likely that these short-term impacts will remain the medium through which any long-term change is felt. The thesis of this paper is, therefore, that impacts from climatic change should be expressed as *changes in risk* of impact from the short-term anomalous event. One advantage of considering possible impacts from climatic changes in this form is that they can be expressed in a language understood by the policy-maker. Present-day frequencies of climatic events can be used as a base upon which to impose effects, such as CO_2-induced warming, to obtain modified frequencies reflecting the possible impacts of costly, extreme events (such as droughts, floods, cold spells, etc.). Government programs can then be devised to accommodate specified tolerable levels of risk, by adjusting activities as necessary to match the change in risk.

In this paper we explore the extent to which levels of climate-related risk have varied in the past, as indicated by the instrumental record. Our choice of data and study area was governed by two requirements: firstly, for a long instrumental record (to detect impacts from short-term changes in patterns of climatic variability); secondly, to examine a region where climatic risk is high, and where changes in climatic risk would have a readily detectable effect on the economic system. Subsequently, with a deeper understanding of the issue, an investigation of this kind can be extended to regions where climatic risk is less pronounced but nonetheless still important.

The longest instrumental record available is that for temperature in Central England compiled by Manley (1953, 1974). This is representative of inland locations in the English Midlands at about 150 feet (46m) above sea level. At this elevation, however, levels of climate-related risk for agriculture are not high. For a convenient laboratory, we thus need to look at upland areas with higher levels of risk. An appropriate one is the Southern Uplands of Scotland which previous work has indicated as being characterized by highly marginal forms of arable agriculture (Parry, 1975). We shall focus specifically on the cultivation of oats which, at elevations of about 340 m in southern Scotland, is near its physiological limit.

However, the instrumental record for this region extends back only to 1856. Only at Edinburgh is it extant for the 18th century (from 1764). For the period before 1764 we must look to the data for Central England available from 1659. By bridging between the data sets for Central England and Edinburgh, and between those for Edinburgh and our upland region, it is possible to derive a 323-year run of temperature data for southern Scotland. We shall analyze these data for long-term changes in climatic risk, first in Central England and subsequently in southern Scotland, and assess the impact of these changes on marginal agriculture in the upland region.

2. Long-Term Variations in Growth Potential

2.1. Selection of the Parameter

In maritime upland areas relatively small increases in altitude generally result in marked foreshortening of the growing season and a great reduction in the intensity of accumulated warmth (Manley, 1945). Moreover, the variability of accumulated warmth relative to the mean increases with altitude, and further contributes to the rapid altitudinal fall in potential for crop growth (Manley, 1951).

For oats, which is more tolerant of high rainfall, frequent soil waterlogging and greater soil acidity than are wheat and barley, the intensity of growing season temperatures is the single most limiting climatic factor. The most effective measure of this is one of accumulated temperature (or the number of growing degree-days, GDD). Growing degree-days are calculated as the excess of mean monthly temperature ($\bar{t}_i$) over the base temperature (t_b), multiplied by the number of days in the month (m_i) and cumulated over one year to give an annual total (A):

$$A = \sum_{i=1}^{12} m_i (\bar{t}_i - t_b) \qquad \text{for } \bar{t}_i \geq t_b \qquad 1)$$

We have used a base of 4·4°C, one established from phenological studies as being appropriate for oats in northern Europe (Nuttonson, 1955), to calculate annual accumulated temperatures for Central England from 1659 to 1981.

2.2. Central England Accumulated Temperatures, 1659–1981

Central England temperatures were assembled by Manley from several discontinuous series into a table of monthly means. This was derived from the average of data recorded in Oxford and at a number of stations in Lancashire from 1815. Data for the period from 1771 to 1815 were obtained by averaging the departures for each month at a number of inland stations whose records are sufficiently long to be "bridged" into the later run of data. For the period before 1771 data were bridged into the record from a variety of scattered observation points.

From these monthly data accumulated temperatures in month-degrees were calculated by Manley (1951) for the period 1751-1949 for sites at a height of 183 m in the English Pennines. However, using the full run of data, we have calculated growing degree-days at 46 m (the height represented by the Central England temperature data) for a 323-year period (Figure 1).

2.3. The Chronology of Accumulated Warmth

The history of these accumulated temperatures is, in one sense, a barometer of the buoyancy of the local farming economy, particularly in the cold, marginal uplands of northern Europe where agriculture is so constrained by a growing season which is both short and lacking in intensity. The most important events in this chronology (bearing in mind that it represents lowland conditions) were probably the cooler-than-average years, particularly those with less than 90 percent of mean accumulated warmth (about 1660 GDD). We can classify these extreme occurrences into: (1) those that are single, isolated extremes (e.g. 1740, 1782, 1860, 1879, 1922); (2) those that represent clustered, successive events of two, three or even more extremes in a row (e.g. 1673-75, 1688-98, 1838-40, 1887-88, 1891-92); and (3) those that represent periods characterized by a high frequency of scattered, not successive negative extremes (e.g. 1812-17, 1879-92). Though not necessarily mutually exclusive, these could have recognizably different effects: the isolated event having a sudden but short-lived impact, while successive extremes bring about increasingly greater economic hardship.

For example 1740 saw a spectacularly poor harvest in Scotland, yet food shortages were made good the following summer (Parry, 1978). Similarly, the cool summer of 1782 delayed the upland oats harvest until December. In Aberdeenshire farmers had to shake the snow off the crop before cutting (Pearson, 1973). Yet there was little lasting hardship.

The limited impact of such isolated events can be contrasted with the effects of a run of extreme years which, by forcing farmers to consume their seed stocks or spend their cash reserves, could seriously prejudice their harvests in subsequent years. In this respect, the effect of the so-called "Seven Ill Years" of the 1690s on the rural population in northern Europe was catastrophic. In Finland at least a quarter, and possibly a third, of the population died in the Great Famine of 1696-97 largely as a result of epidemic diseases spreading through an ill-fed and weak population (Jutikkala, 1955).

Finally, we can detect the cumulative, erosive effect of the periods characterized by frequent, but scattered extremes. In these instances, the process of recovery was halted and reversed by a series of recurrent shocks that, over several years, the farm economy had insufficient stamina or resilience to absorb. In the U.K. the scattered extremes over 1879-92 slowly brought more and more farmers to a state of bankruptcy, particularly because grain prices, held back by cheap imports since the repeal of tariffs on North American grain, failed to respond to depressed yields (Perry, 1974; Royal Commission, 1883).

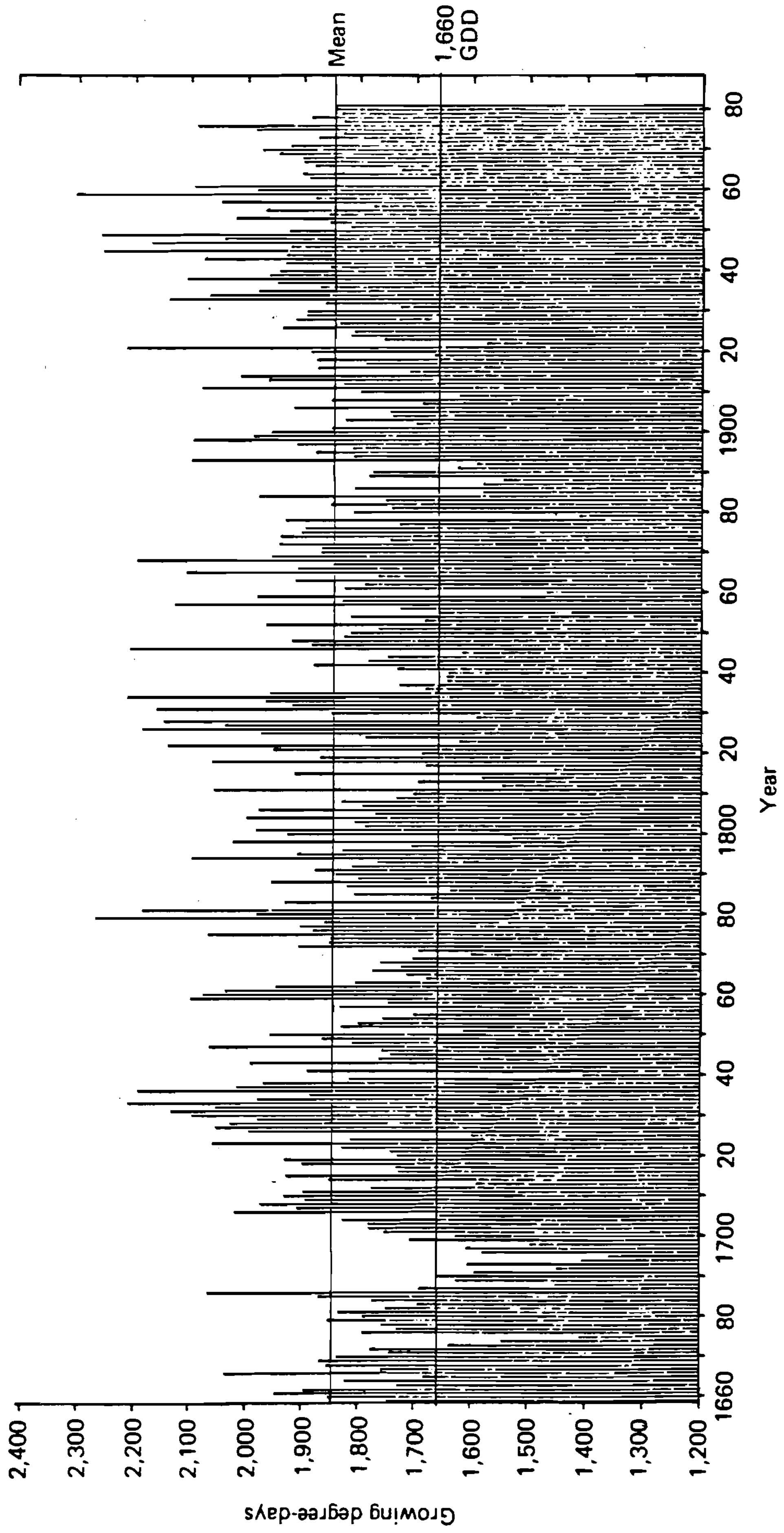

Fig. 1. Annual growing degree-days at 48m above sea level in Central England, 1659–1981. Base temperature is 4·4°C.

Such historical, ideographic descriptions of the effects of single, successive, and clustered extremes are, however, not a sufficient basis for generalizations concerning the impact on agriculture of climatic variability and of changes in that variability. Such a basis can only be provided by study of specific responses in particular farming systems. We shall focus specifically on the probability of crop failure because we believe that this is a most effective measure of impact from climatic variations. There are two reasons for this. Firstly, marginal farmers, by definition, operate near the limits of profitability and are more concerned with survival (i.e. probability of their avoiding failure) than with accumulating wealth (i.e. their increment above a minimum average condition). Secondly, the non-marginal, profit-maximizing farmer knows well that net returns are not simply a function of average yield, but also of the balance struck between gambling on "good" years and insuring against "bad" ones (Edwards, 1978).

We shall focus on those changes in probability of crop failure that can occur as a result of changes of climate. To do this, however, requires a long run of data. These are obtained by bridging across to our upland study region from the Central England temperature record.

2.4. Derivation of Proxy Accumulated Temperatures for Southern Scotland

A 323-year proxy record of accumulated temperatures for southern Scotland was constructed by bridging from Central England to Edinburgh, and from Edinburgh to a network of 27 stations covering the study area.

2.4.1. Bridging from Central England to Edinburgh

Data for the period of overlap between the two records (1764-1896) were analyzed to establish linear regression equations, for each month, of Edinburgh temperatures on Central England temperatures. Correlation coefficients were also recorded, and all indicate a close relationship between the two sets of monthly temperatures (significant at the 99 percent level). A plausible means of extrapolating the Edinburgh record is, therefore, to use the regression coefficients as predictors of temperatures at Edinburgh for the full period, 1659-1981.

2.4.2. Bridging from Edinburgh to Southern Scotland

Twelve regression equations relating mean monthly temperatures to elevation were calculated, one for each month, from the 40-year record (1856-1895) for the 27 stations (excluding Edinburgh) in southern Scotland. These equations were used to estimate monthly means (1856-95) for a site representative of the whole region at the same altitude as the Edinburgh station (76 m). The differences between these estimates and the actual monthly means for Edinburgh, were then used as correction factors to adjust the proxy Edinburgh data to obtain longer-term temperatures for the study area. We can thus derive a 323-year set of accumulated temperatures for southern Scotland, within which to examine the frequency of crop failure.

3. The Frequency of Crop Failure

3.1. Method

For many crops the point of "failure" is an arbitrary one because, however small the return of grain, the residue material (straw, etc.) is often valuable as fodder. There is a point, however, where the grain yield falls so far short of the expected yield or the yield required to cover costs of inputs such as seed, labor and fertilizers that, in economic terms, the year's venture may be considered a failure. Clearly crop failure can thus be defined in many different ways, each appropriate for different farming systems and crop types.

Our definitions and data for crop failure refer to Red and Blaislie varieties of oats which were commonly grown in the study region in the nineteenth century. By examining diaries and farm journals for that period we can identify the years of crop failure and, by referring to the meteorological record, the weather of those dismal summers. Empirically, it had been concluded from earlier work that where accumulated temperatures failed to exceed 970 degree-days oats harvests were extremely delayed and reduced (Parry, 1978).

Knowing the lapse rate of temperature with elevation in the region (0.68°C/100 m, Parry, 1976), it is possible to calculate, for each year, the height at which the minimum accumulated temperature is achieved. Above this height, which shifts upwards and downwards substantially from year to year according to variations in accumulated warmth, the oats crop would have been long delayed (Figure 2). We thus have a picture, for the period 1659 to 1981, of the year-to-year shifts in the hypothetical upper limit of the oats crop caused by annual variations in temperature. In this way, climatic variations can be expressed as the spatial variation of a boundary, which shifts across an economic surface: thus a farmer who in one year lies on the "right" side of the boundary and, *ceteris paribus*, has an oats crop to harvest, may in another lie on the "wrong" side and recoup very little. It is but a simple step to express that farmer's position in terms of risk of crop failure due to inadequate accumulated warmth and, furthermore, to express climatic changes as changes in that level of risk. Before doing so, however, it is useful to explore the value of Figure 2 as a predictive tool in historical research and, in so doing, to provide some verification of the model.

3.2. Predicting the Location of Crop Failure

Following the tripartite classification introduced earlier, we can predict the locations at which crop failure occurred either in individual extreme years or in successive extremes, or in periods with particularly frequent extremes. Where adequate historical information is extant, the predictions can be tested against historical actuality.

As an example of the predicted impact from a single, isolated extreme we can predict that in the cool summer of 1782, farms located above 300 m (see Figure 2) would have experienced failed oats harvests. There is some confirmation of this from a contemporary account for the high-lying parish of Lauder which reports that "It was the end of December before the harvest was finished, after a great part of the crop was destroyed by frost and snow. None of the farmers could pay their rent; some of them lost two hundred to five hundred pounds sterling" (Statistical Account of Scotland, 1791-99). There were some farm bankruptcies, with the subsequent amalgamation of holdings, but unlike the effect of successive extremes in the 1690s, the parish returns for the Statistical Account reported little sign of lasting hardship in the 1790s resulting from that single dismal summer in the preceding decade.

As for the clusters of consecutively cool summers, three would have caused consecutive failure above 300 m: 1674-75, 1694-95 and 1816-17. More substantial runs of failure would have occurred at higher levels. For example, above 340 m failure would theoretically have occurred in eleven successive years from 1688-98 (Figure 2). This elevation approximately matches the actual upper limit of oats cultivation in the seventeenth century, so we can hypothesize that the highest arable farmer in southern Scotland saw failure for 11 continuous years in the 1690s. In fact, a comparison of the manuscript Pont maps dating from about 1596 with those of the Military Survey of Scotland of 1747-55 indicates that few of those high-lying farms survived: of 32 recorded in about 1600, only 10 remained in the

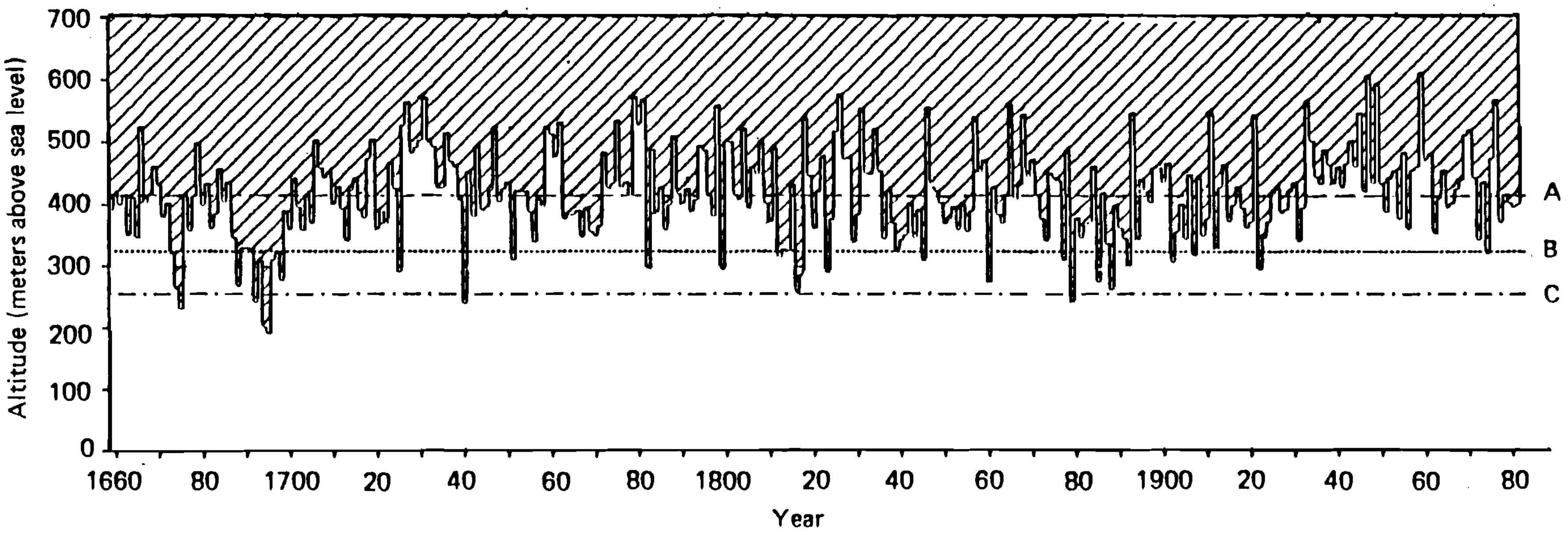

Fig. 2. Hypothetical shift of oats crop failure with altitude in southern Scotland, 1659–1981. A, mean altitude of crop failure; B, 1-in-10 failure frequency; C, 1-in-50 failure frequency.

next century.

Less immediately marked but probably as enduring in their effects were the periods of more frequent (though scattered) extremes. The late nineteenth century is an appropriate example. For this period our calculations (Figure 2) point to harvest failure at elevations exceeding 310 m for 5 years out of the 16 between 1877 and 1892. At these high levels adverse weather and depressed prices were reflected in the long-term transfer of arable to permanent grassland and rough pasture. Official annual acreage returns for the region reveal a 5 percent reduction in the area under crops and grass between 1880 and 1885, and reductions of about 1 percent every five years from 1885 to 1900.

It is not the aim of this paper to describe these historical impacts in any detail. The complicated task of disentangling the relative roles of climate, economic and social factors is a matter for more lengthy treatment elsewhere. Yet it is apparent from the preceding discussion that, by reference to a long run of instrumental weather data that have been reformulated into altitudes of crop failure, it is possible to identify for any particular year or period, the areas most seriously affected by variations in accumulated temperature.

4. A Risk Surface of Crop Failure

With increasing elevation, the decrease in temperature clearly imposes a greater restraint on cultivation, increasing the probability of inadequate accumulated warmth and crop failure. In an earlier paper (Parry, 1976) we had assumed annual totals of accumulated warmth to be normally distributed, and found a strongly nonlinear relationship between altitude and risk of crop failure, the probabilities increasing almost exponentially at certain heights (Figure 3). Subsequently we referred to this as an assumed "risk surface" and emphasized that one important effect of changes in climate could be to change the location and inclination of this risk surface (Carter and Parry, 1984). We can now discard the assumption of normality and, by considering the *real* surface of risk over the 323-year period for which we now have data, can estimate the *changes* in the probability of crop failure that have occurred during this long period.

Actual occurrences of crop failure (i.e. years with less than 970 GDD) for the period 1659-1981 in southern Scotland were calculated for 10 m intervals. These are plotted as frequencies of single and two consecutive failures in Figure 3. The curved lines indicate the corresponding theoretical frequencies for normally distributed temperatures. A comparison of actual and theoretical frequencies indicates a risk surface for single failures that is approximately normal, but a distinct clustering of cool years results in a steeper than normal risk surface for consecutive failures. At 340 m (which is approximately the limit of cultivation in the region) the real frequency of consecutive failures is more than double that of the assumed frequency. In some respects, then, the real risk surface is steeper than expected.

5. Delimiting High-Risk Areas

It is also possible to delineate, on the basis of this long run of data, a high-risk zone in which oats is near its physiological limit and where probabilities of failure are very high. Isopleths of crop failure frequency reveal the distribution of these areas (Figure 4). For the present we shall adopt the frequencies of 1-in-10 and 1-in-50 as delineating the upper and lower edges of the high-risk zone. Ideally the choice of frequencies would be based empirically upon behavioral surveys at the farm level. But, whatever are the critical frequencies for certain farming decisions, the effect of altitude on levels of risk is much the same. For example, on the gentle slopes of the southern part of the study area the probability of crop failure doubles over a distance of only about 5 km (Figure 4).

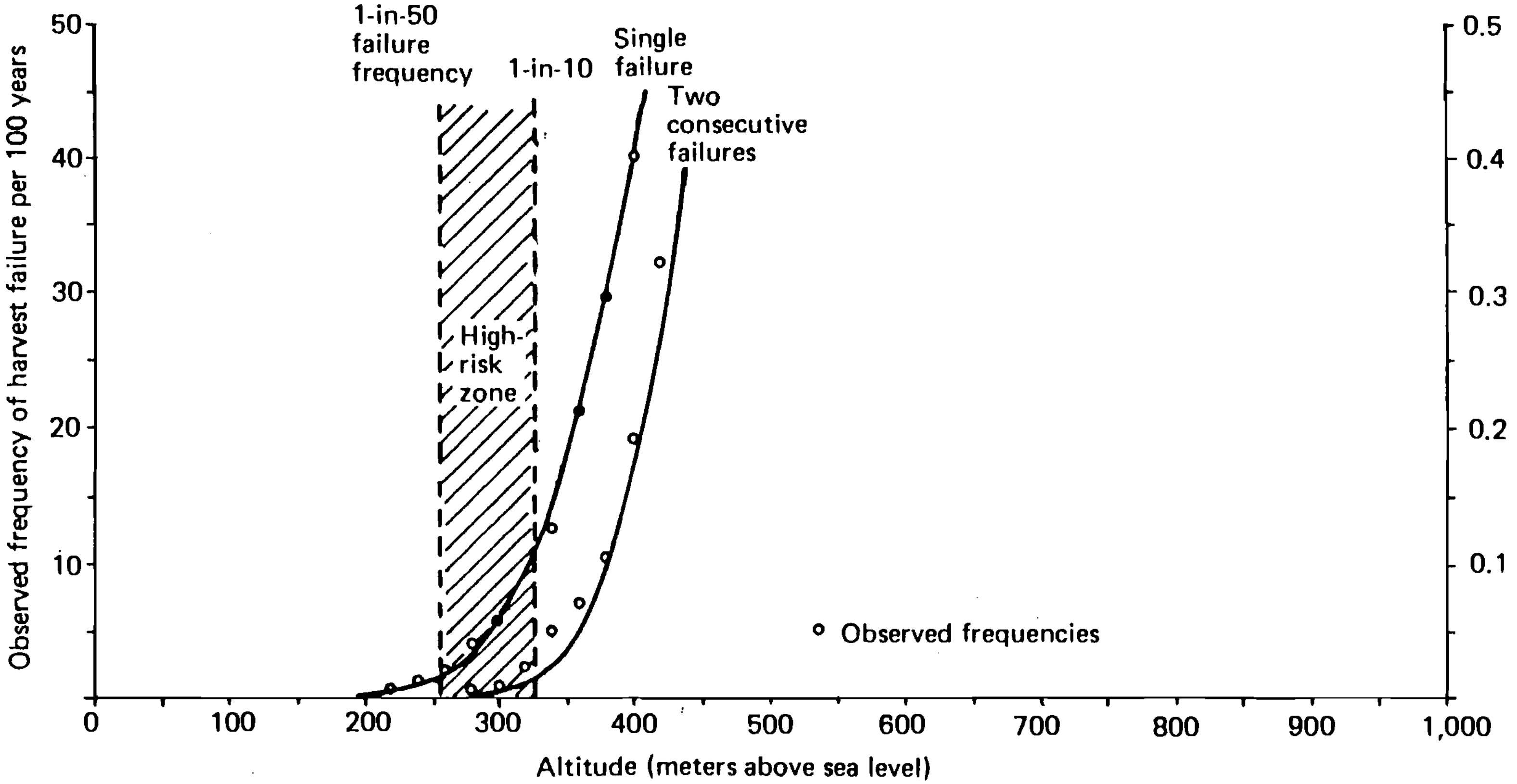

Fig. 3. Actual and assumed frequencies of harvest failure (annual growing degree-days below 970) in southern Scotland, 1659–1981. Curves indicate frequencies assumed for a normal distribution of accumulated temperatures.

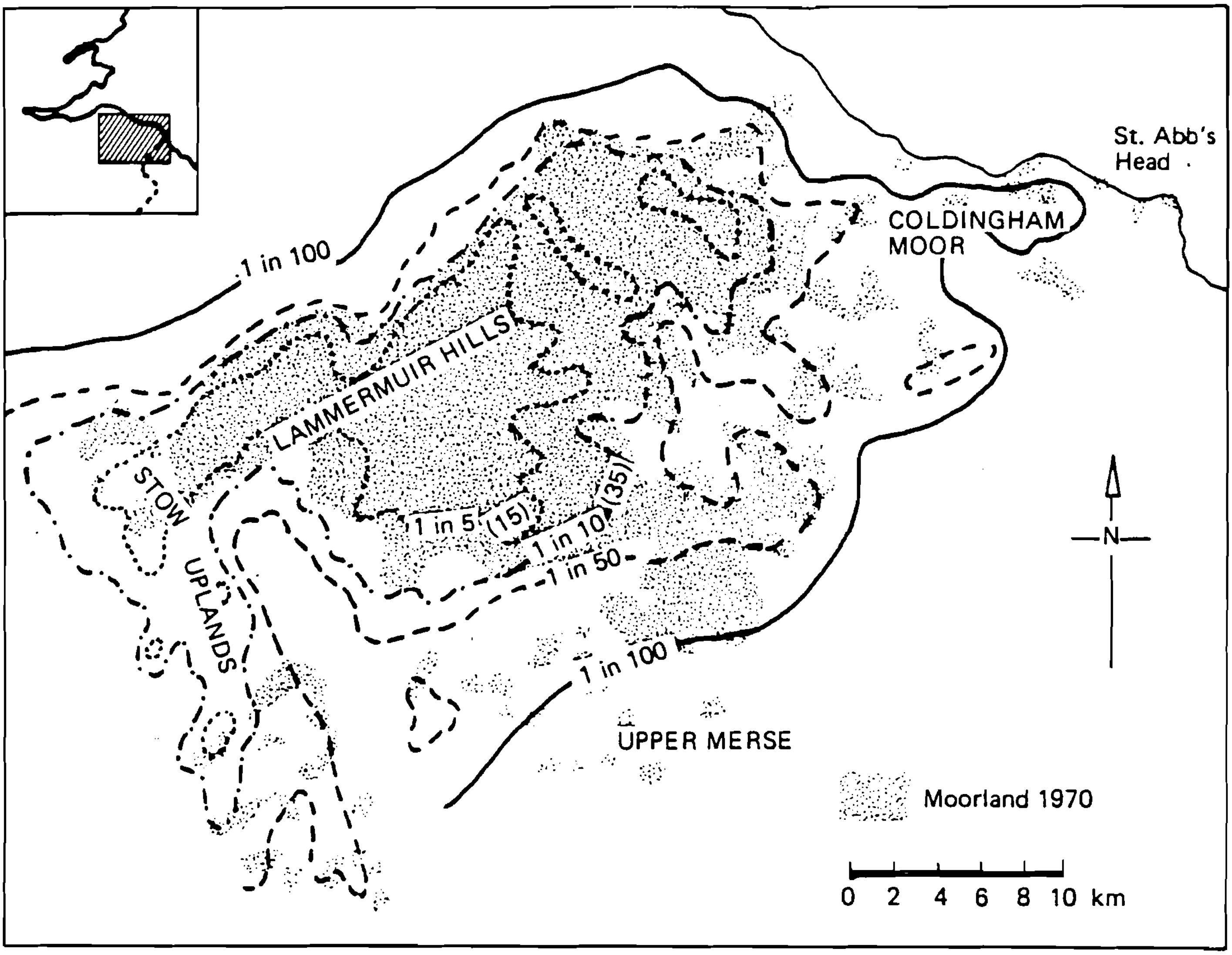

Fig. 4. Isopleths of actual frequency of crop failure in southern Scotland as defined by years with less than 970 GDD. Figures in parentheses indicate actual frequency of 2 consecutive failures.

6. Changes in the Frequency of Crop Failure

The risk isopleths of 1-in-10 and 1-in-50 are average frequencies derived from the 323-year record. However, it is clear from Figure 1 that accumulated temperatures have varied greatly from one period to another, and Figure 3 indicates that these would have produced significant spatial shifts of the limit of crop failure. It follows that the high-risk zone is not static but, depending on the time-scale of study, apparently shifts from year to year, decade to decade, and century to century. A perturbation in the climate can thus be expressed as the shift of such a risk zone.

To evaluate the effect of temperature variations that have occurred over the past 300 years, we have determined the risk surface and high-risk zone for cool and warm 50-year periods in the record (1661-1710 and 1931-80, respectively), and have analyzed their shift between these periods.

The shift of the assumed risk surface is considerable, as illustrated by the curves in Figure 5. Furthermore, the shift of *real* frequencies (plotted as points) is greater still due to the higher-than-expected failure frequency in the cool period concurrent with fewer-than-expected failures in the warm period.

The altitudinal movement of the high-risk zone exceeds 85 m, such that the line of 1-in-50 frequency for the recent warm period lies above even that of the 1-in-10 frequency for the cool period, at the nadir of the so-called "Little Ice Age". In geographical terms, the location of this zone has been radically altered (Figure 6). While in the late seventeenth century a substantial proportion of the foothills (above about 280 m) were submarginal to the cultivation of oats, the climatic limit of cultivation for the modern period stands on average at 365 m, representing an additional 150 km^2 of potentially cultivable land.

7. Conclusions

We have considered elsewhere the possible connection between changes of climate and changes in the use of marginal land (Parry, 1978). Those connections were analyzed on the basis of *estimated* 50-year averages of temperature, the argument being that long-term changes in climate were the changes that, if any, had an enduring economic effect. However, the present analysis of yearly data based on mean monthly temperatures has revealed the importance of the short-term event, particularly of extreme years. It has emphasized that an important path of impact from change in average climatic conditions is a change in the frequency of extreme events. Changes in this frequency can be expressed in terms of a shift of the risk surface or of critical boundaries of risk.

We have not sought to establish these critical levels empirically. That remains to be done, but there are grounds for accepting the 1-in-50 frequency of crop failure as an approximation of the limit to viable cereal farming in the study region. For example, its isopleth for 1931-80 coincides with the present limit of cultivation, or "moorland edge"; a fairly stable boundary that reflects an adjustment of agriculture to prevailing economic and environmental conditions, and an adjustment that operates on a decadal rather than an annual or secular scale.

If there were a simple causal relationship between climatic risk and the cultivation limit then, *ceteris paribus*, we would expect both to have shifted in sympathy. Not surprisingly the actual relationship is far from simple and there are many intervening factors. Nevertheless, the shifts of risk level and growth potential (or of other derived parameters that have not been considered here) can be taken as a prediction of impact on agriculture; a prediction that can be tested against historical records and then, if necessary, reformulated. Subsequently it should be feasible to improve our predictions of impacts from possible future

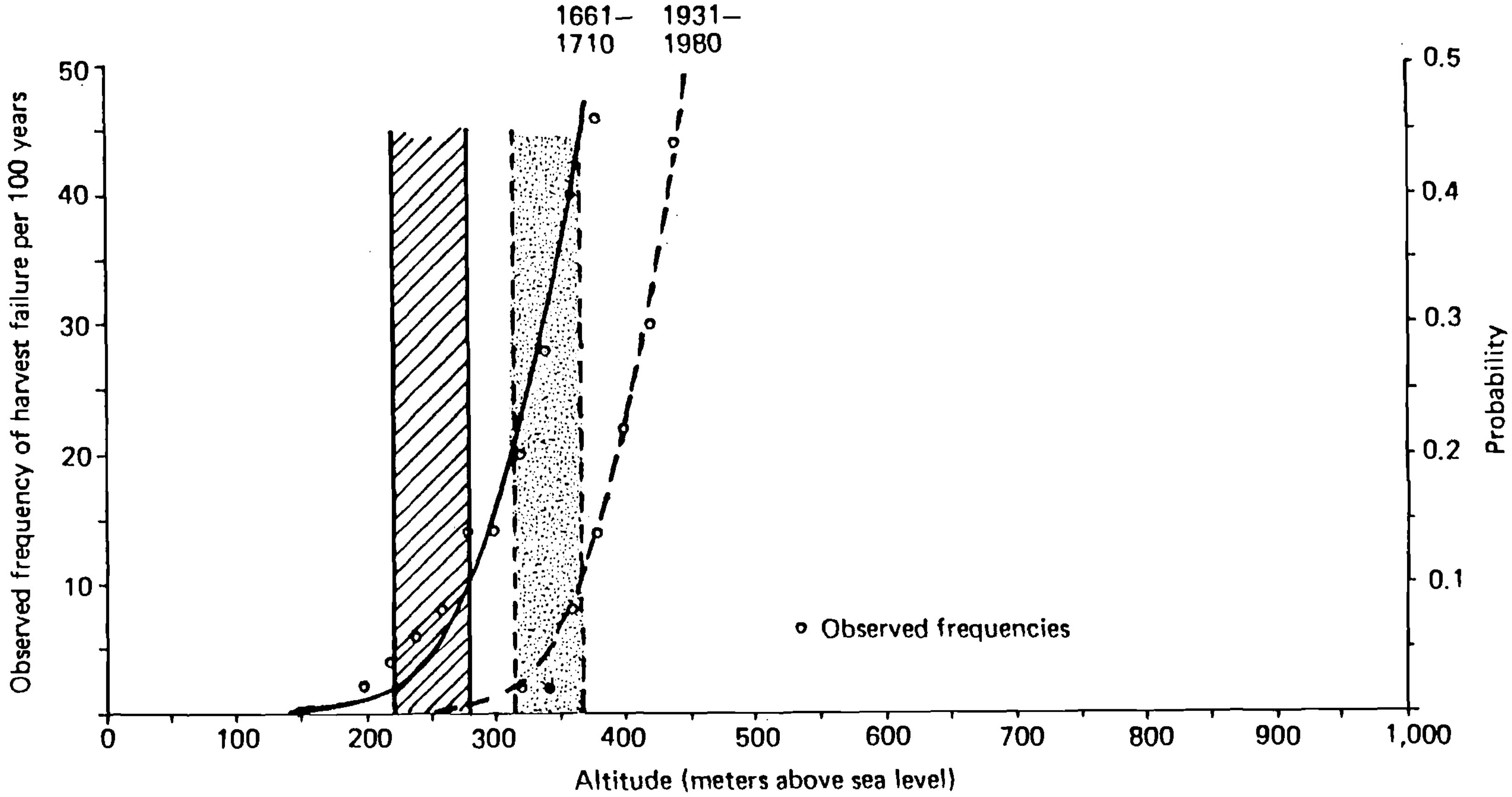

Fig. 5. Differences in the risk surface of crop failure for the cool (1661–1710) and warm (1931–80) 50-year periods in southern Scotland. Shaded and stippled areas denote "high-risk" zones.

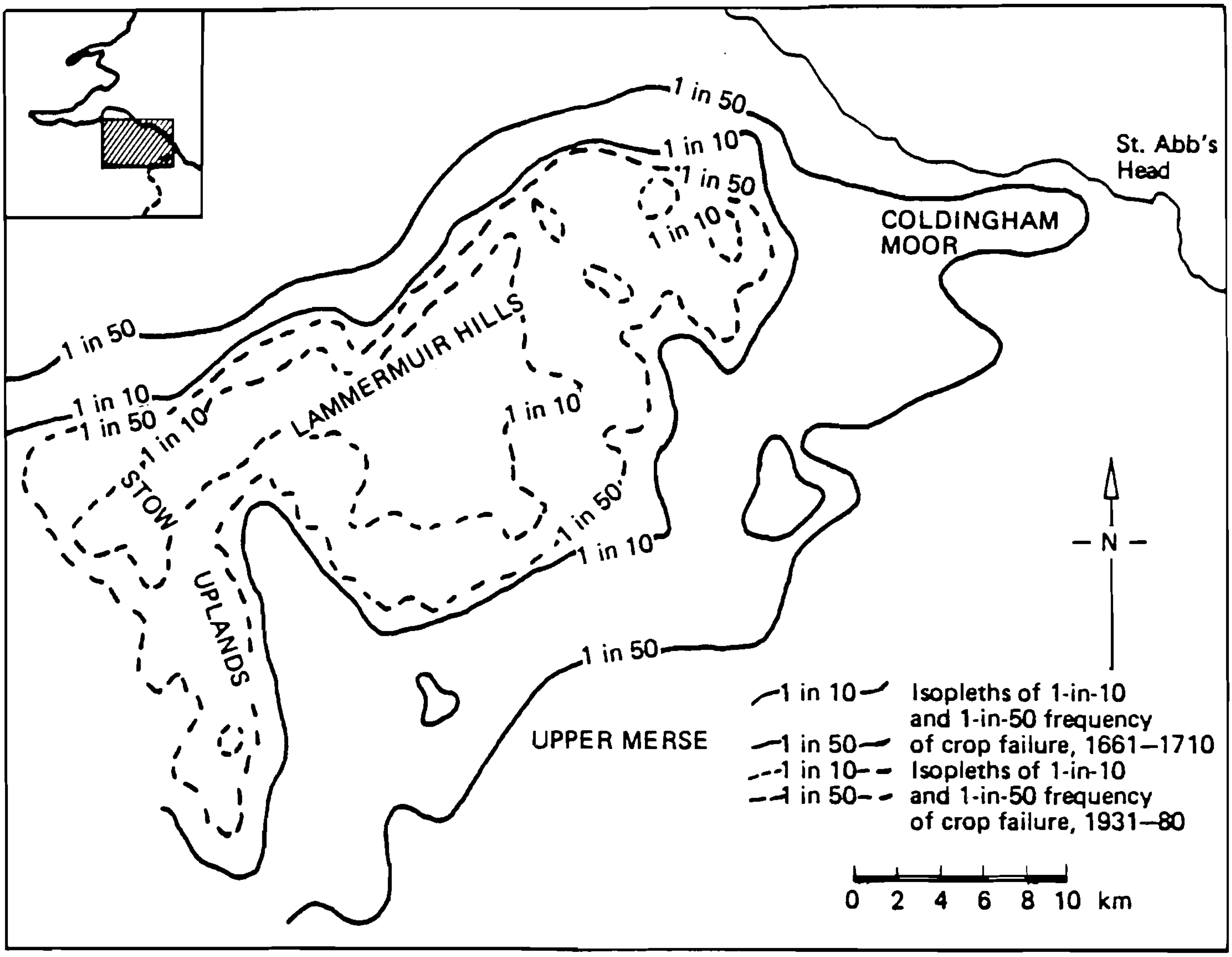

Fig. 6. Locational shift of a high-risk zone between the cool (1661–1710) and warm (1931–80) periods. Risk is expressed as frequency of oats crop failure.

changes of climate by expressing them as changes in the frequency of extreme events and, thus, as changes in level of risk. One advantage of this approach is that, as an adaptive measure, agricultural support programs could be re-tuned to accommodate acceptable levels of risk by adjusting support levels to match the change in risk. More generally, we may conclude that if changes of risk are an important possible consequence of climatic change, then we need to measure the frequencies of occurrence of extreme events under present (normal) climatic conditions and to use these frequencies as a base upon which to superimpose the effects of a possible future climatic change, to obtain modified frequencies of occurrence of such anomalies.

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