SCOPE 27 - Climate Impact Assessment

14 The Impact of Climatic Variations on Agricultural Margins

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14.1 INTRODUCTION

Human activities, within the constraints of accessibility and the competition of other more valued activities, are generally located in areas favourable for their practice. Over time the fit is usually improved upon by various adaptive actions. As the most favourable areas are taken up, activities expand to their margin, where they are barely worthwhile or barely compete with other activities. Here, at the margin, the impact of climatic variability can be more pronounced, and marginal areas may thus be appropriate `laboratories' for studying the interaction between society and climate. That is the thesis of this chapter.

Over the past decade or so, several researchers have evolved relatively sophisticated methods for assessing climatic impacts in marginal areas. Their studies, some of which I shall describe below, give some assurance to the assessment of the nature, scale and location of impacts which might be expected for certain types of climatic variability and climatic change.

14.1.1 Definitions

We can identify three types of marginality—spatial, economic and social. The first relates to locations and areas where activities are at the edge of their ideal climatic region, for example, where warmth or moisture is barely sufficient to enable an adequate return from a particular type of farming. In a sense these areas are akin in their sensitivity to the ecotone (or transition zone in tension between two communities), which has frequently been employed by the biologist as a laboratory for the study of ecological change. In the case of farming, many such margins are determined economically as much as climatically—they mark the boundaries of comparative advantage between competing farming types (for example, between the corn belt and the wheat belt in the United States). But climatic change can bring about shifts in economic margins as well as in biophysical margins. The important point is that climatic impacts can be expressed as shifts of the margins (farmers changing their farming systems or abandoning farming entirely). For the climatic impact analyst, margins are lines or zones between arbitrarily defined classes which undergo a spatial shift for given climatic variations, and thus provide an indication of the type and location of impact.

In reality there are other types of marginality which can complicate this form of analysis: *economic marginality*, where returns to a given activity barely exceed costs, and *social marginality*, where groups are isolated from their indigenous resource base and are forced into economies which contain fewer adaptive mechanisms for survival (Baird *et al.*, 1975). These provide two further dimensions to the spatial one: while spatial marginality implies differentiated environmental resource complexes, different economic resources and different political power can allow different access to the environmental resources.

To start with we shall simplify this real-world complexity by considering only spatial marginality. We review methods available for identifying marginal areas at risk from short-term climatic variations or longer-term climatic changes, outline a general research strategy, and exemplify some variants of this strategy to illustrate how it can be employed to identify the location of areas of increased impact.

14.2 STRATEGIES FOR IDENTIFYING IMPACT AREAS

On the face of it, similar impacts may occur as a result of quite different factors. For example, adjustments in agriculture may occur from changes in farming objectives (such as levels of expectation or tolerance levels), changes in farming systems (in technology, labour, demand) and changes in the agricultural resource base (such as soil erosion, climatic change). These three groups of factors (and others not considered here) are sometimes closely interconnected. The problem is to disentangle them so that we can specify, with some confidence, the effects of climatic change and variability.

One way to tackle this problem is to attempt a prediction of the areas and types of impact on the basis of an understanding of the interactions between agriculture and weather, and then proceed to test these predictions against historical actuality. It will subsequently emerge that different studies in different regions of the world have, for obvious reasons, employed variants of this strategy to suit their local circumstances, but the overall approach has remained broadly the same. There are four steps in this approach:

1. to isolate the important climatic variables by modelling crop/climate relationships;

2. to establish critical levels of these variables by relating them to farming behavior (such as through changes in the probability of reward or loss);

3. to resolve climatic fluctuations into fluctuations of the critical levels (such as probabilities); and

4. to map these as a shift of isopleths to identify impact areas.

14.2.1 Modelling Crop/Climate Relationships

In order to have any confidence in an assessment of likely changes in agricultural output that would occur as a result of certain fluctuations in climate, we need to ascertain the weather variables which account for most variability of yield now (that is, under `normal' or 'unperturbed' conditions).

14.2.1.1 Isolating the Weather Variables

Various means of analysing crop/climate processes have been discussed by Nix (Chapter 5, this volume). We can distinguish three types of models:

1. crop-growth simulation models (which attempt to represent the physical, chemical and physiological mechanisms underlying plant- and crop-growth processes);

2. crop/weather analysis models (which attempt to represent the functional relationship between certain plant responses—for example, yield—and variations in selected weather variables at particular stages of plant development); and

3. empirical-statistical models (which seek to identify those weather variables which show a strong association with crop yield by virtue of high correlation coefficients).

Each of these models has varying data requirements and disadvantages in assessing impacts over long rather than short time-scales, but they at least provide some scientific basis for impact assessment.

14.2.1.2 Selecting Critical Levels of Weather Variables

By specifying levels of the climatic variables which correspond to apparently critical biophysical margins of certain crop types, or critical margins of yield or profitability, it is possible subsequently to evaluate climatic impacts as shifts of such margins. Both the variables and their levels will, of course, vary according to different farming systems and crop types. For example, at high levels in southern Scotland the oat crop is especially sensitive to exposure, and the warmth and wetness of the growing season. By an empirical study of crop limits, critical levels were established as being 6.2 m/sec average windspeed, 60 mm potential water surplus, and 1050 degree days above a base of 4.4 °C (Parry, 1975).

On the Canadian Great Plains, the northern margin of cereal growth is controlled by temperature and photoperiod. A biophotothermal time-scale has been established for wheat (Robertson, 1968) and barley (Williams, 1974) to determine the region within which these crops would normally reach various phenological stages: at the northern boundaries of each region the crops would be expected to ripen by first freeze in 50 out of 100 years (Williams and Oakes, 1978). It has also been possible to compute where, on average, the crops would ripen 0–20, 20–40, and more than 40 days before first fall freeze (Williams *et al.*, 1980). In a similar fashion Uchijima (1978) has drawn isopleths of minimum effective temperature for rice cultivation in northern Japan.

14.2.2 Climate and Farming Decisions

The selection of supposedly critical levels of climate variables for agriculture assumes a knowledge both of what is critical to the crop (such as levels of warmth, moisture and sunshine) and what is critical to the farmer (such as levels of yield, profit and the like). Thus far we have considered only what is critical to the crop. In order to assess impacts on agriculture we need to ask: to what exogenous perturbations is the farming system most vulnerable? For example, to changes in average yield or changes in minimum yield? To the probability of profit or loss? And what levels of these? Once again, our assessment should consider the different levels of vulnerability and different responses which tend to characterize different farmers and farming systems.

14.2.2.1 The Probability of Crop Failure, Net Loss or Critical Shortfall

Previous studies have tended to focus on climatic impacts on average yields. There are several reasons, however, for believing that changes in the probability of success or failure due to climate variability are more important to many marginal farmers than changes in average yield. First, marginal farmers, by definition, operate towards the limits of profitability, have a slender buffer against hardship, and thus are more concerned with survival than with wealth. Their strategies emphasize risk avoidance rather than maximizing outputs. Second, even the profit-maximizing farmer (including those in nonmarginal areas) 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 ensuring against `bad' ones (Edwards, 1978). Third, the boundary between profit and loss for particular farming activities over the medium or long term may depend on the relative frequencies of favorable and adverse weather; for example, a major constraint on profitable wheat production in Alberta is related to the probability of first autumn freeze occurring before the crop matures (Robertson, 1973).

The appropriate measure of this kind of impact is likely to vary from place to place. Among noncommercial farmers it may be failure to give a minimum yield. Among commercial farmers it may be the balance between inputs and outputs (for example, net loss) or some measure of shortfall below the expected yield (for example, 10 percent below average).

14.2.2.2 The Probability of Consecutive Impact

Marginal farmers may be especially vulnerable to losses in successive years. Consecutive harvest failures, by removing the reserve of seed corn, have been taken as a cause of famine in subsistence communities in the past, and today, at the international level, consecutive failures can lead to a sudden and marked drop in food reserves that is difficult to make up by increases in productivity or by the extension of the cultivated area, except over the longer term. The chance of two successive shortfalls (90 percent of average output) in US foodgrains production is certainly not insignificant. Sakamoto *et al.* (1980) estimate it to be 9 percent.

Moreover, the probability of the occurrence of two extremes in consecutive years is far more sensitive to a change in mean climatic value than is the probability of the single occurrence. To illustrate, consider a numerical example and suppose that extremely cold winters or dry summers occur with a probability of $P = 0.1$. The return period for the occurrence of a single extreme is, therefore, 10 years, while the return period for the occurrence of two consecutive extremes is 100 years (assuming a normal distribution of frequencies). Any change in climate will lead to a change in P, either through changing variability which will change P directly, and/or through a change in mean conditions that must also change P if extremes are judged relative to an absolute threshold. Alternatively, P may change through changes in some critical impact threshold as a result of land use changes, new crops or crop mixes, increasing population pressure, and so forth. If P becomes 0.2, then the return period for a single severe season is halved to 5 years. The return period for consecutive severe seasons, however, is reduced by a factor of four to only 25 years.

We may conclude that, in certain cases, climate impact on agriculture can appropriately be expressed as changes in the probability of some critical occurrence or, in other words, as a change in risk. This notion can be incorporated in the overall strategy so that changes in the frequency of critical levels of selected weather variables are expressed as a shift of isopleths of the probability of risk or reward. The strategy may be summarized as a flow diagram (Figure 14.1). In this example the weather, described by a set of meteorological data for a number of years, is expressed as a probability of crop failure. When calculated for a number of stations this probability level can be mapped geographically as an isopleth. Scenarios of changing climates can then be used as inputs to the model to identify geographical shifts of the probability isopleths. The area delimited by these shifts represents areas of specific climatic impact. The method will now be illustrated by reference to a case study in upland Europe, where the major limiting factor to cereal cropping is summer warmth.

14.2.2.3 Calculating the Frequency of Failure, Loss or Critical Shortfall

At many locations the climatic variables that influence rates of plant growth (such as temperature, precipitation, sunshine) decrease in a roughly linear fashion towards the margin of cultivation. For example, in areas where cereal cropping is limited largely by temperature (namely at high latitudes and high elevations), accumulated warmth decreases approximately linearly with increasing elevation and increasing latitude. While this is, of course, a generalization, the point is that, assuming annual levels of warmth or moisture to be normally distributed from year to year, the *probability* of a minimum level of warmth or moisture required to avoid failure, loss or critical shortfall would increase, not linearly towards the margin of cultivation, but in the S-shaped curve characteristic of the cumulative frequency of a normal distribution (Figure 14.2). At the lower end of this curve there is a marked, indeed quasi-exponential, increase in the probability of failure, and it will be shown that it is precisely at this part of the curve that marginal land is frequently located. It seems, therefore, that marginal areas are frequently characterized by a very steep `risk surface'. A consequence is that any changes in average warmth or aridity, or in their variability, would have a marked effect on the level of risk. In reality, the interannual distribution of warmth or moisture is frequently non-normal, so the real levels of risk may be even higher.

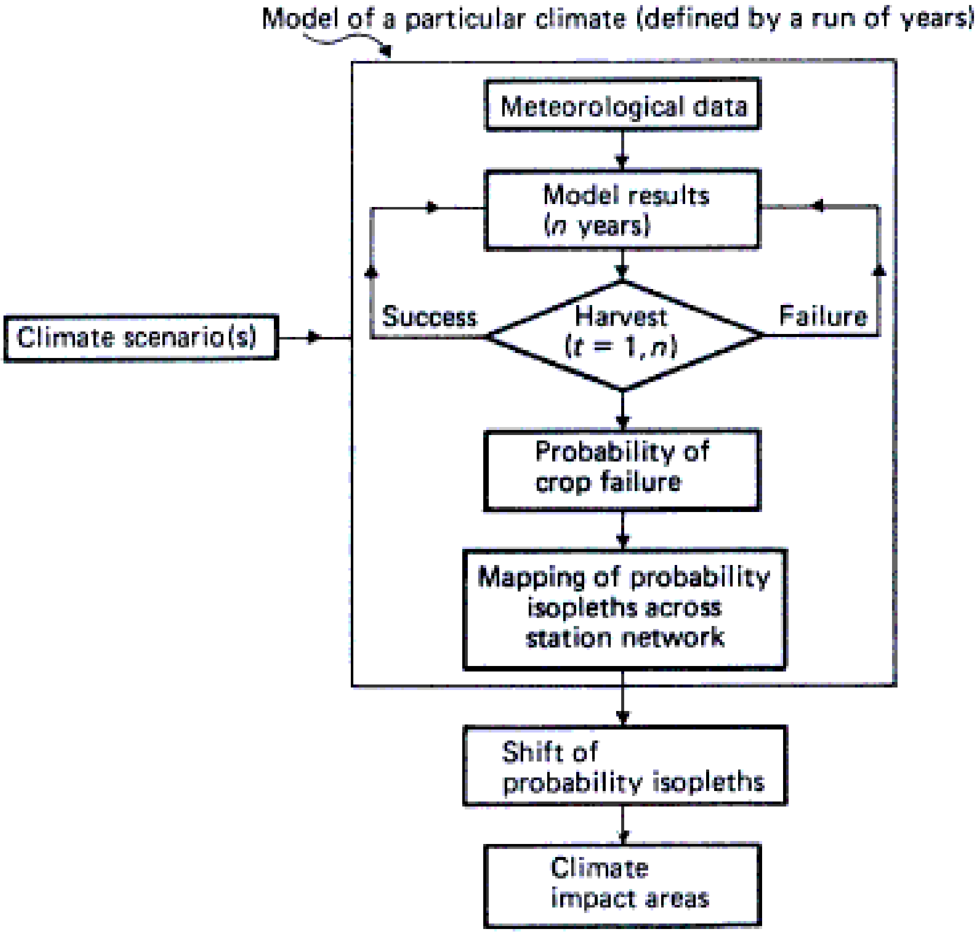

Figure 14.1 Steps in the identification of climate impact areas. (After Parry and Carter, 1983)

To illustrate, in southern Scotland, where the main constraint on cereal cropping is the intensity of summer warmth, the oat crop (variety Blainslie) will not mature before mid-September in growing seasons of less than 970 growing degree days (Parry, 1975). The frequency of this type of crop `failure' increases quasi-exponentially with elevation, in a fashion similar to that described in Figure 14.2. It follows that changes in temperature over time (due to a change in climate rather than a shift of location) have a magnified effect on levels of risk: at the margin of cultivation (about 300 metres) in Scotland a 0.5 °C reduction in mean monthly temperature would, *ceteris paribus*, lead to a 10 percent fall in accumulated warmth, a doubling in the probability of crop failure, and a *six- fold increase* in the probability of two successive failures (Parry, 1976). This result would hold for an equal decrease in each monthly mean across the whole growing season. An increase in variability would further magnify the probabilities.

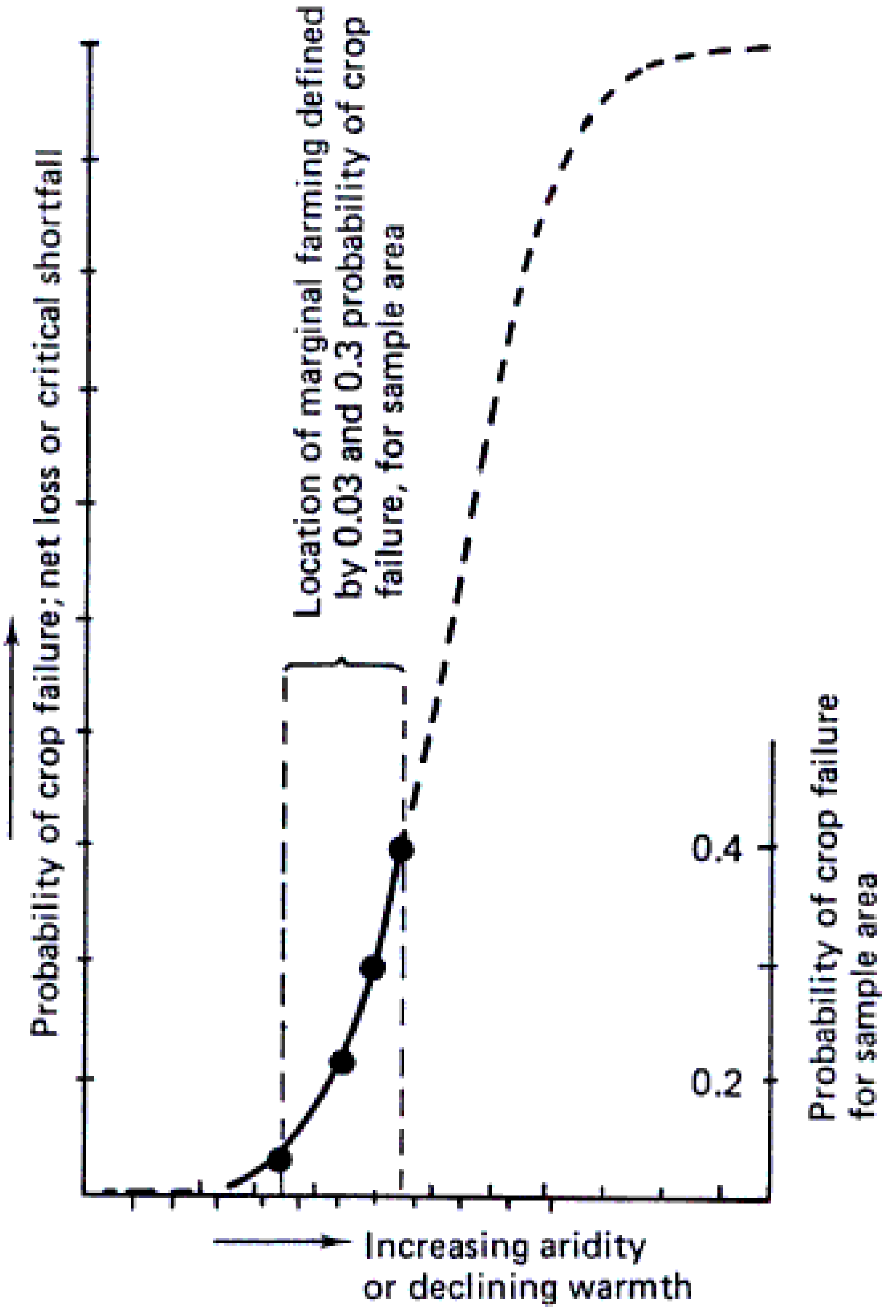

Figure 14.2 Probability of crop `failure', net loss or critical shortfall, with linear (and normally distributed) gradient of aridity or warmth. Sample area is S. Scotland, probabilities of crop `failure' are for oats (var. Blainslie). Probabilities of crop failure which define the marginal areas are derived from empirical data on farming strategies in S. Scotland. (Adapted from Parry, 1976)

From a study of the temperature lapse rate with elevation we can also gauge the gradient of the risk surface: at an elevation of about 200 metres in Scotland the frequency of crop failure increases 100 times with only a 150-metre increase in elevation. From meteorological data that enable us to estimate the different lapse rates in different regions, it is possible to map areas of climatic risk by drawing isopleths of tolerable levels of crop failure. The levels of tolerance need to be based upon some empirical assessment (such as interviews with farmers) that takes account of local social and economic factors. As an example, the levels chosen for oats cropping in Britain were frequencies of failure of 1 in 3.3 and 1 in 33—between these levels oats cropping as an enterprise was taken to be highly precarious (Parry, 1978). Isopleths of these risk levels (Figure 14.3) point to areas where this type of agriculture is especially sensitive to climate. The next step is to examine what shift of these isopleths occurs for specified changes of climate.

Figure 14.3 Areas that are marginal for oats cropping in the British Isles. Calculated from data relating to temperature requirements for the ripening of oats (var. Blainslie). (After Parry, 1978)

14.3 IDENTIFYING AREAS OF IMPACT

The method can be illustrated by reference to case studies at the margin of cultivation in upland Europe, central Canada, the southern US Great Plains and northern Japan.

14.3.1 Upland Britain

Using the method described for southern Scotland, and constructing isopleths of a crop failure frequency of 1 in 3.3, we can analyse the shifts of these isopleths which occur for a specified temperature change (or a variety of possible temperature changes). In northern Britain a 1 °C increase in mean monthly temperature throughout the growing season would, *ceterus paribus*, lead to approximately a 140-metre upward shift of the probability isopleths regarded as critical for successful oats cropping (a failure frequency of 1 in 3.3) (see Figure 14.4). Across the British Isles as a whole there would be regional variations in this shift, due both to latitude and to variations in the lapse rate of temperature with elevation. In total about 2 million hectares (about one-third) of Britain's unimproved moorland, which are at present submarginal for cereals in terms of summer warmth, would become marginally viable for cereal farming (Parry, 1978).

14.3.2 The Canadian Prairies

Similar use of the shift of critical isopleths has been made in two independent studies of the effect of a 1 °C downturn in temperature on Canadian wheat production. At the Land Resource Research Institute (Ottawa), Williams and others have used biophotothermal time-scale equations for wheat (Robertson, 1968) and barley (Williams, 1974) to estimate if and when these crops would normally reach various phenological stages at each of 1100 stations in Canada (Williams and Oakes, 1978). The data also were used to calculate the normal first fall freeze dates and the number of days from ripening to first fall freeze. Extrapolation between these stations enabled isopleths of the limits for three phenological stages (heading, soft dough stage and ripening) to be drawn for Olli barley and Marquis wheat. To compute the climatic resources for a cooler climatic regime, 1 °C was subtracted from the temperature normals for every month. This made the assumed planting date later, extended the time required to mature as computed by the biophotothermal time-scale equations, and brought forward the date of first fall freeze. Figure 14.5 illustrates the shift of isopleths bounding the wheat-maturing zone: the area suited to wheat production (not constrained by soil or terrain) would be reduced by one-third. The area suited for barley would contract by only one-seventh because it extends farther north and therefore is more limited by terrain than by temperature. These are, of course, average estimates; no account has been taken of changes in the degree of risk.

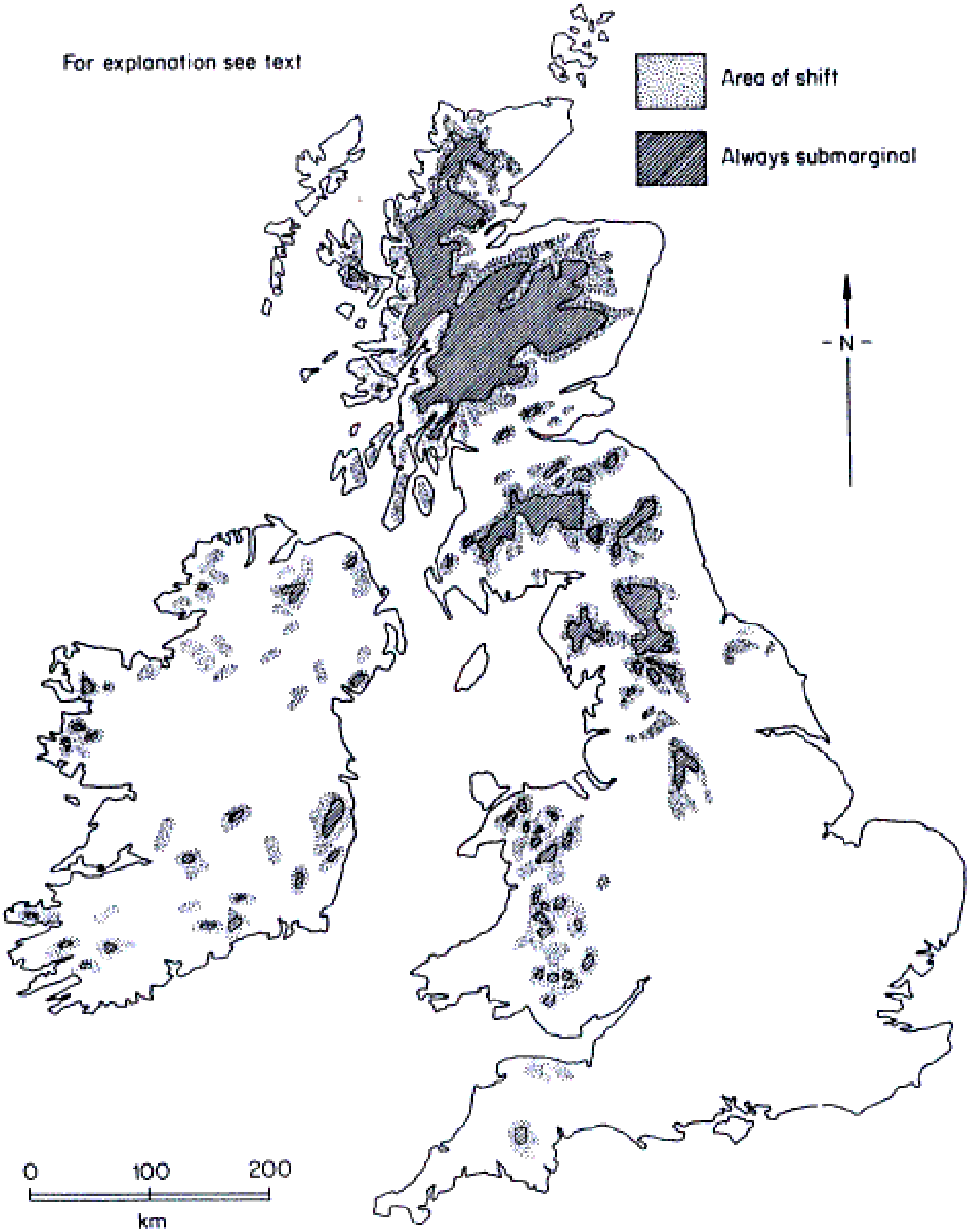

Figure 14.4 Shift of 1 in 3.3 failure frequency for oats in the British Isles for 1 °C increase in mean annual temperatures (normals 1856–95)

A similar, though unpublished, study in the Environmental Systems Branch of Environment Canada gave more attention to changes in the *probability* of ripening (Winstanley, 1974, personal communication). The study concluded that a decrease in mean annual temperature of 1 °C would reduce the frost-free

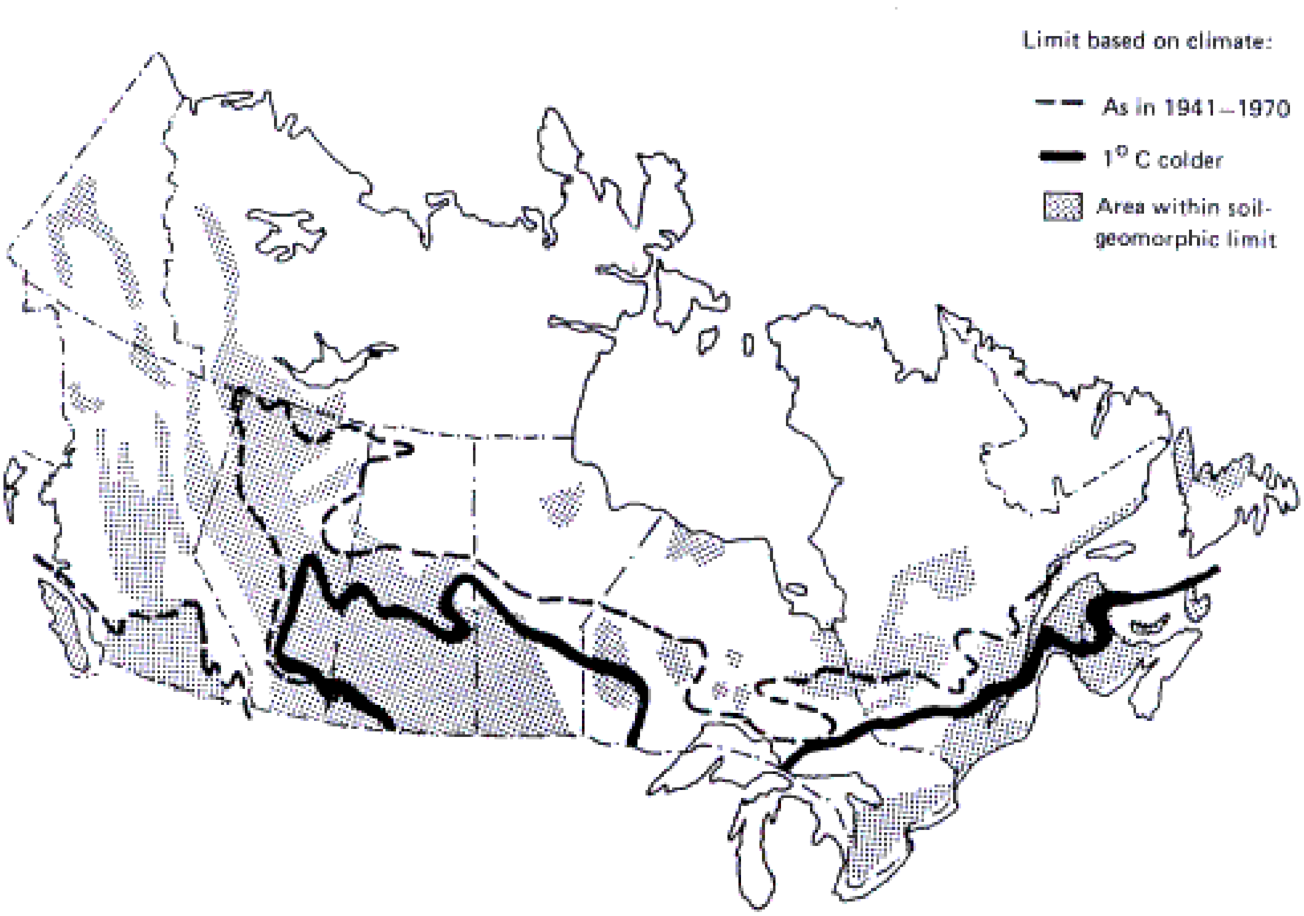

Figure 14.5 Effect of 1 °C cooling on wheat limit in Canada. (After Williams and Oakes, 1978)

period in southern Canada by about 10 days but, by decreasing mean annual degree day totals by 4─6 percent, would increase the time needed for ripening by 4─6 days. This change would effectively reduce the frost-free period by about 15 days, thus increasing the probability of frost kill before crop maturity. Although slightly lower temperatures would tend to reduce moisture stress in some areas and thereby increase average yields, a shorter growing period would reduce the already small margin between maturity and first fall frost, and thus greatly increase the risk of total crop failure.

14.3.3 The US Corn Belt

A third variant of the isopleth-shift approach can be illustrated by reference to the work of Newman (1980) on the US Corn Belt. Newman applied daily differences of ±1 °C to growing degree days (GDD) for 18 stations in Indiana over a 10-year period and determined that the average north─south distance between isolines of 1600 GDD for the three different conditions (normal, +1 °C and ─1 °C) was 144 km per degree C. He also calculated the effect of a temperature change on potential evapotranspiration (PET), concluding that a 1 °C change in mean annual temperature in Indiana produced a change of 5.9 cm in annual PET. These values translate into a west─east shift of approximately 100 km in annual PET values per degree C. The 100 km west─east shift in annual PET coupled with the 144 km north─south shift of the 1600 GDD line per degree C were used to estimate the geographical shift in the corn belt per degree

C. Figure 14.6 illustrates the simulated shift for a 1 °C warmer and drier climate, which is a plausible scenario for the future, given continued increases in the CO_2 content of the atmosphere, and for a 1 °C cooler and wetter climate, which is a plausible simulation of conditions which probably occurred for some cool decades in the seventeenth century.

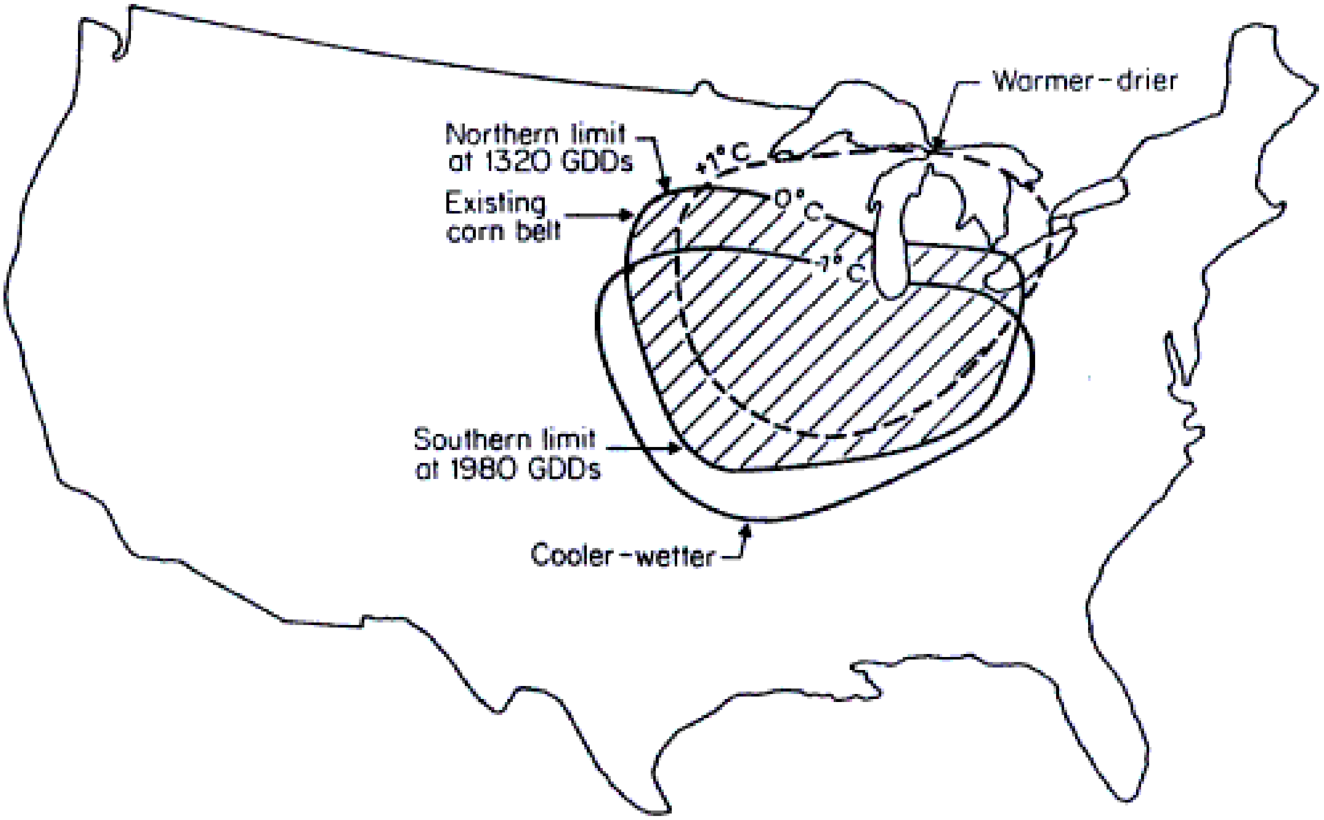

Figure 14.6 Simulated geographical shift in the US corn belt with temperature changes (based on frost-free growing season thermal units, GDDs). (After Newman, 1980)

14.3.4 Northern Japan

It may be more realistic to predict the maximum and minimum thermal resources which can be expected in a given period by calculating a return period using ordered data on GDD and growing season. In Japan, Uchijima (1978) found that the magnitude of the possible maximum and minimum GDD and growing season increases linearly with the increment of the coefficients of variance for these fluctuations. The isopleths of GDD in the southern, middle and northern parts of Japan could be expected to shift southward by 150, 200 and 300 km, respectively, if an anomalistic decline in temperature expected every 30 years should occur. Such a southward shift in the isopleths of GDD would cause a reduction in rice production in the Hokkaido district by about 40 percent, but would have much smaller effects further south. The conclusion, once again, is that the risks stemming from climatic variability increase markedly towards the margins of cultivation.

14.4 TESTS AGAINST HISTORICAL ACTUALITY

Insofar as it is possible to use climatic episodes of the past as approximate (but by no means perfect) analogues of a future scenario, it is possible to test predictions against the actuality of impacts in the past. The problem is that changes in technology make the scenarios difficult to compare; the scale and type of impact could be very different in the future than they were in the past. But at least the *location* of the impacts is likely to be comparable.

In southern Scotland there is a close temporal and spatial fit between the distribution of permanently abandoned settlements and farmland and the predicted `fall' of theoretical climatic limits to cultivation between AD 1600 and 1800 (Figure 14.7) (Parry, 1975). Since the predicted correlation was derived theoretically and empirically from estimates of process links, it is logical to assume that the observed correlation reflects some kind of causal connection between climatic change and land abandonment.

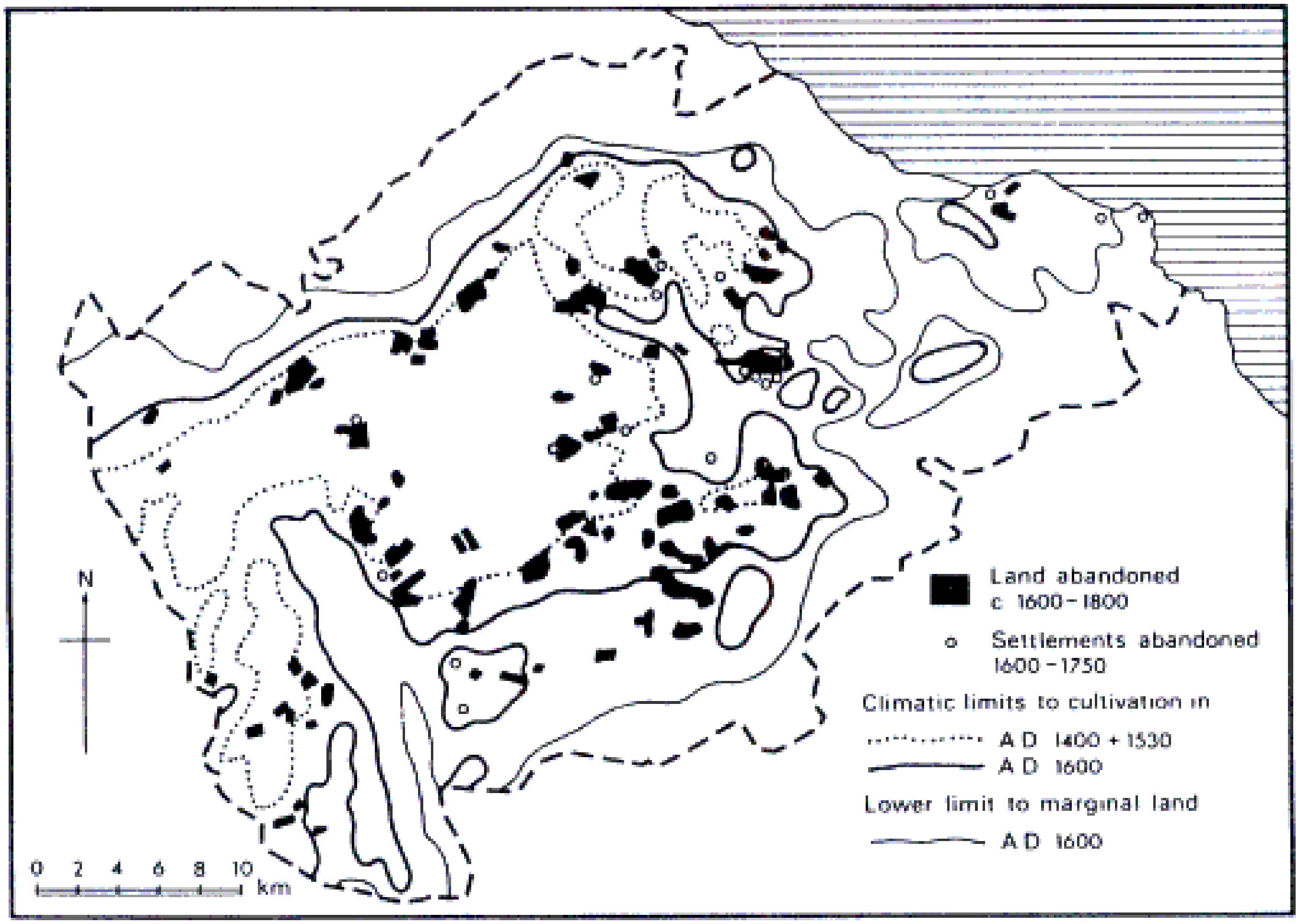

Figure 14.7 Abandoned farmland and lowered climatic limits to cultivation in southeast Scotland, AD 1600–1750. (After Parry, 1975)

One problem, however, in making historical tests of predicted impact is that the evidence for historical shifts in agriculture and settlement has frequently been used to reconstruct past climates. To test the predicted impact of climate change against `response' in agriculture and settlement would thus be to invite criticism of a circular, or at least elliptical, argument—although this has unfortunately not discouraged some from trying.

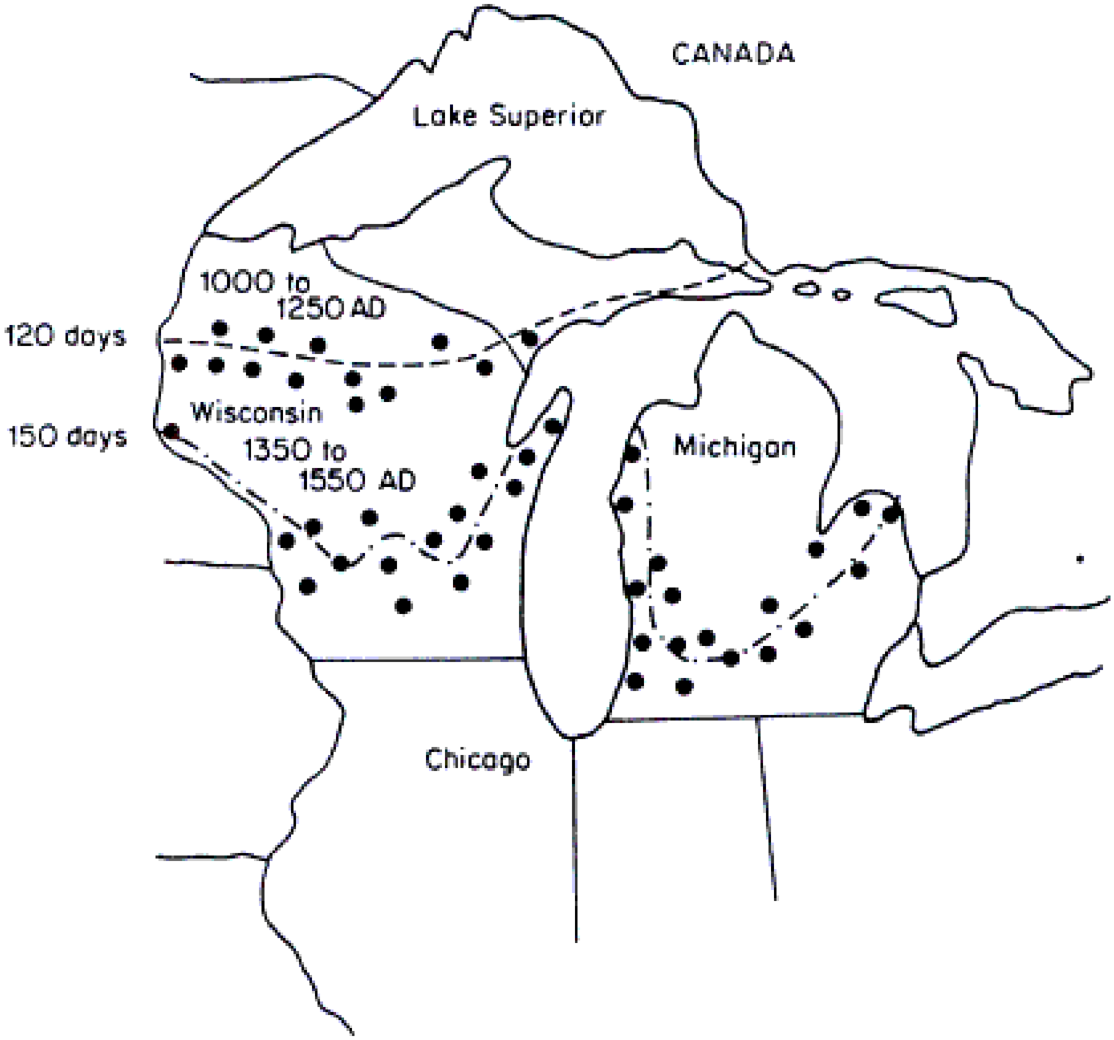

Figure 14.8 Distribution of prehistoric ridge-furrow maize gardens in relation to present-day frost-free seasons. Reproduced by permission of Swets Publishing Service from Newman (1980), *Biometeorology,* **7**, 128-142 (on p. 137), after Riley and Friemuth, *American Antiquity*, **44**, 271-285 (1979)

One region for which there may be sufficient and `uncontaminated' evidence for impact is in the upper Great Lakes region of the United States. The northern limit of prehistoric maize fields appears to have retreated up to 320 km southward concurrently with cooling in the thirteenth and fourteenth centuries (Figure 14.8) (Riley and Friemuth, 1979; Newman, 1980). At present we must be content to class this as a `space–time' coincidence, but it does seem to mirror Newman's simulated shifts in the Corn Belt which would occur with a 1 °C fall in mean summer temperatures.

The impact of cooling on early agriculture may, however, be more readily detectable than the impact of drought, probably because it is both temporally and regionally less variable. Studies of impact in cold marginal areas thus hold the greater prospect of reward. Early indications of success are now emerging from work on Greenland (McGovern, 1980) and Iceland (Ogilvie, 1981).

14.5 CONCLUSION

This chapter has outlined a strategy for assessing the impact of climatic exchange in marginal areas. It has emphasised the need to

1. isolate the important climatic variables by modelling crop weather processes,
2. establish critical levels of these variables by relating them to farming decisions via changes in the probability of reward or loss
3. resolve climatic fluctuations into fluctuations of these probabilities, and
4. map these as a shift of isopleths to identify impact areas.

A number of examples have been presented to illustrate how the method can be implemented. Each of these examples has exhibited some local and perhaps unique characteristics, but the contention is that the overall strategy is one which has wide potential application.

In conclusion, we should restate two important *caveats* and introduce a new one. First, the term `margins' have been used here to describe boundaries of arbitrarily defined classes (for example, land-use types, average yield levels, frequencies of crop failure). Marginal areas are not always `poor' areas. They are areas delimited by a set of criteria such as those described above. Thus, land at the wheat/corn boundary in the United States is not *intrinsically* marginal land (that is in terms of its fertility, etc.). It happens to be located where the concerted influence of present-day environmental, economic, social and other forces leads to a finely balanced competition between wheat and corn. The thesis of this paper has been that finely balanced margins of this kind can provide us with sensitive measures of climatic impact.

Second, we have not considered how different economic and social resources allow different access to environmental resources. Those in farming, as in other walks of life, may be rich or poor, good managers or poor managers, risk-averse or risk-taking. Such variety is bound to place many new dimensions on the issues we have discussed and, at local levels, factors like these would certainly need to be considered.

Finally, there is no suggestion here that it is possible to predict areas of climatic impact on the basis of global interpretations emerging from climatic history. One approach has been described, modified for certain case studies, and, in some instances, tested against the past. Wherever else it is applied, it would require a similar degree of modification to suit local problems and local data.

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