Working Paper

ASSESSING IMPACTS OF CLIMATIC CHANGE
IN MARGINAL AREAS: THE SEARCH FOR
AN APPROPRIATE METHODOLOGY

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PREFACE

The coevolution of mankind and the biosphere is one of today's principal research problems. Clearly, human activity has begun to rival nature's ability to modify the variability of the earth's climate or even to generate climatic changes. Human intervention into the climatic system could have profound consequences for the biosphere, and thus careful analysis and consideration of both the environmental and societal implications of such intervention are critically needed.

For the past several years, researchers at IIASA have been examining problems such as these. In 1978, for example, a meeting was held on "Carbon Dioxide, Climate and Society". This meeting brought together experts from around the world to assess the state of knowledge on the prospects of climate change resulting from increasing atmospheric injections of carbon dioxide and in particular to review work on this subject in the IIASA Energy Systems Program. In the same year, IIASA hosted the International Workshop on Climate Issues organized by the Climate Research Board of the US National Academy of Sciences and a preparatory meeting for the World Climate Conference organized primarily by the World Meteorological Organization (WMO) of the United Nations. In 1980, a Task Force meeting on the Nature of Climate and Society Research was convened to advance our knowledge of the relationship of climate to specific aspects of physical and social systems. More recently, in 1982, an international workshop on "Resource and Environmental Applications of Scenario Analysis" was organized. This workshop focused on innovative approaches for dealing with issues like climatic change which involve considerable uncertainty and multidisciplinary analysis. Finally, a major 2-year project is currently being initiated with the support of the UN Environmental Programme. This project will investigate the impacts of short-term climatic variations and the likely long-term effects of CO_2-induced climatic changes on agricultural output at the sensitive margins of food grains and livestock production.

This paper sets the stage for the above-mentioned project. It reviews the notion of climate-related marginality, and proposes to measure the impact of climatic fluctuations on marginal areas by a temporal change in the level of risk of harvest failure and spatial shifts of crop pay-off boundaries. The practical usefulness of these measures is illustrated by several case examples from the US, Canada, and Northern Europe. Finally, the paper outlines the crop/climate simulation model, successfully applied for analysis of the effects of possible climatic changes on cereal yields in Northern England. Over the next two years it will be the aim of the IIASA project to further develop this methodology and to evaluate the impact on food production of possible changes in climate.

Janusz Kindler
Leader
Impacts of Human Activities on
Environmental Systems Project

CONTENTS

ASSESSING IMPACTS OF CLIMATIC CHANGE IN MARGINAL AREAS: THE SEARCH FOR AN APPROPRIATE METHODOLOGY

M.L. Parry and T.R. Carter

The overriding problem facing any study of climate and society is the awesome complexity of the interactions. On occasion we have side-stepped this issue and resorted to investigating merely the synchrony of climatic and social events, with little scrutiny of their connection other than that they occur at the same time and in the same place. The assumption has sometimes been that synchronous events are events which necessarily have a causal connection--an assumption which is clearly false. We need to increase the rigour of our research strategy and thus cope with the complexity of the interactions.

One means of (at least partly) achieving this is to employ a predictive approach to climate impacts in marginal areas, assuming that marginal areas are particularly suitable laboratories because they are the first to be affected and the most severely affected by climatic anomalies: i.e., they exhibit a high degree of risk resulting from climatic change and variability. For this reason marginal areas have been selected by the World Climate Impact Program to be the focus of a study conference on CO_2-induced climate impacts (at Villach, Austria, September 1983) and a two-year research project at IIASA on the vulnerability of food production to climatic change.

In this paper we review a number of different strategies for evaluating climate impacts in marginal areas. Our thesis is that changes in climate can usefully be analysed, firstly, as temporal changes in risk and, secondly, as spatial shifts in the probability of pay-off. We will illustrate this contention by reference to a number of case studies, which have been drawn from our own studies and those of other scientists. Full discussion of these examples will not be found in this paper, but is available in the referred literature.

Marginality and climate

We can identify three types of marginality - spatial, economic and social (Figure 1). The first type relates to locations and areas at the edge of their ideal climatic region, where systems of marginal agriculture are frequently ill-adapted to their environmental resource base - for example, where warmth or moisture is frequently insufficient (or, conversely, frequently excessive) for an adequate return to particular types of farming. But whether yield-levels are adequate or barely adequate (i.e. are marginal in an economic sense) is culturally determined - it depends on farming expectations and perceived alternatives. Spatial marginality can thus be resolved into economic marginality. It is also possible to identify marginal groups which, as a result of their social rather than intrinsically economic disadvantage, may be equally vulnerable to unfavourable climatic anomalies or fluctuations. The process which generates this vulnerability has been termed "marginalization" - a process by which the under-developed population is isolated from the indigenous resource base and is forced into marginal economies which contain fewer adaptive mechanisms for survival (Baird et al., 1975). None of these marginal areas or groups is strongly buffered against change of the environment and may thus be particularly sensitive to variations of climate.

Climatic change as change in risk and probability of pay-off

For a number of reasons the impact of climate variations on marginal areas can most effectively be measured as a change in the level of risk, i.e. in the probability of an adverse event such as the probability of crop 'failure', or net loss, or shortfall from some critical level of output. 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. Secondly, the profit-maximising farmer (including those in non-marginal areas) knows well that net returns are not simply a function of average yield, but also of the balance he strikes between gambling on 'good' years and insuring against 'bad' ones

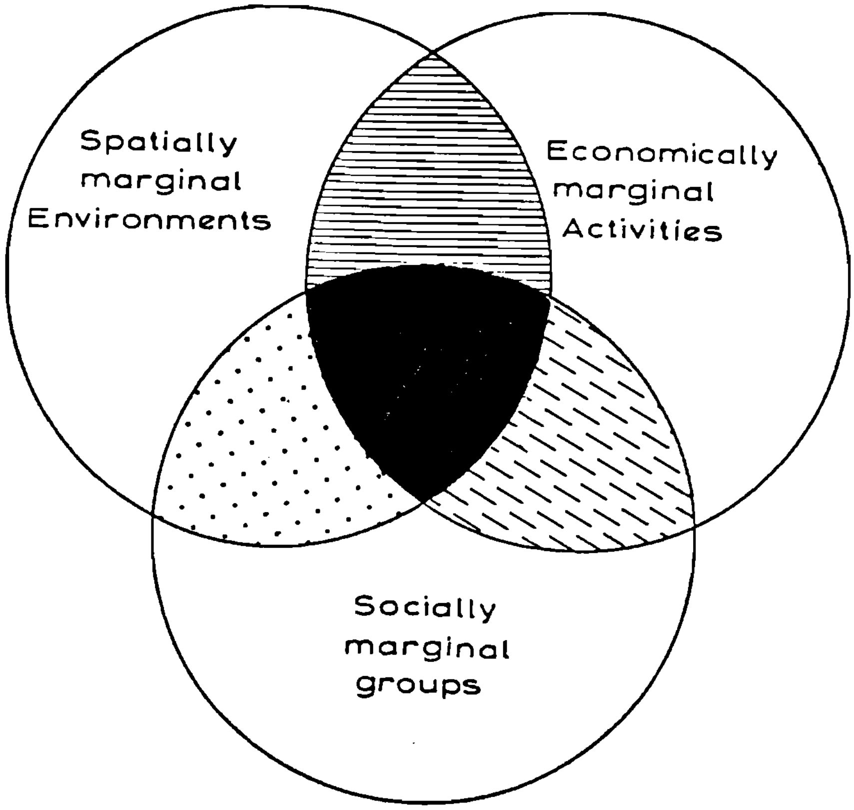


Figure 1. Types of marginality

(Edwards, 1978). Thirdly, the pay-off boundary for particular farming activities may depend on the frequency of 'good' or 'bad' weather; for example, a major constraint on profitable wheat production in Alberta is related to the probability of first autumn freeze (Robertson, 1973). At some locations the parameters of climate which frequently have a major influence on rates of plant growth (e.g. temperature, precipitation, solar radiation) decrease in a roughly linear fashion towards the margin of cultivation. For example, in areas where cereal cropping is limited largely by temperature (viz. 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 an S-shaped curve which is characteristic of the cumulative frequency of a normal distribution (Figure 2). At the lower end of this curve there is a marked

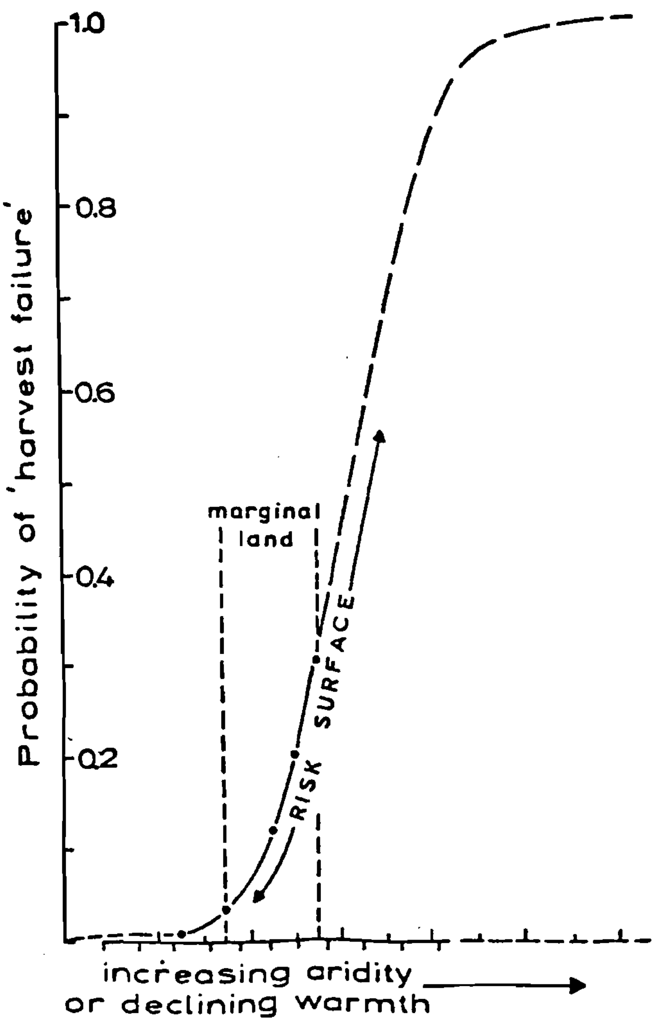


Figure 2. Risk surface due to probability of crop 'failure', net loss or critical shortfall, with linear (and normally distributed gradient) of aridity or warmth. Probabilities of harvest 'failure' are for oats (var Blainslie) in S. Scotland (adapted from Parry, 1976).

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 of this is that any changes in average warmth or aridity, or in their variability, would have a marked effect on the level of risk. The effect can be illustrated by reference to the U.S. and Canada.

a) U.S. Great Plains. On the U.S. Great Plains variability of wheat yield due only to climate can be assessed by comparing yields predicted for specific years by wheat-climate regression models with the expected or average yields of those years allowing for technological change but excluding the role of disease and prices. Figure 3 illustrates, for each crop reporting district in Nebraska, Kansas and Oklahoma, the proportion of years in which the predicted yield exceeds or falls short of the expected yield by 25 per cent or more. It is evident that the risk of shortfall increases markedly from east to west: in south-west Kansas the frequency of a 25 per cent shortfall in 'climate-yield' is more than four times that in the south-east of the State. Moreover, we should note that distribution of good and bad years is evidently lopsided: there is a greater chance of a sizeable shortfall than a sizeable excess, and the losses from drought-years are not likely to be made up by an equal number of single bumper harvests. The real wheat-ranching boundary, which is an expression of adjustment to climate-risk in wheat, broadly follows the 25 to 50 per cent isopleth of serious shortfall of climate-yield. Of course, this boundary is an average one; in reality the boundary of pay-off between wheat and ranching shifts from year to year due to climate variability. We shall examine this later.

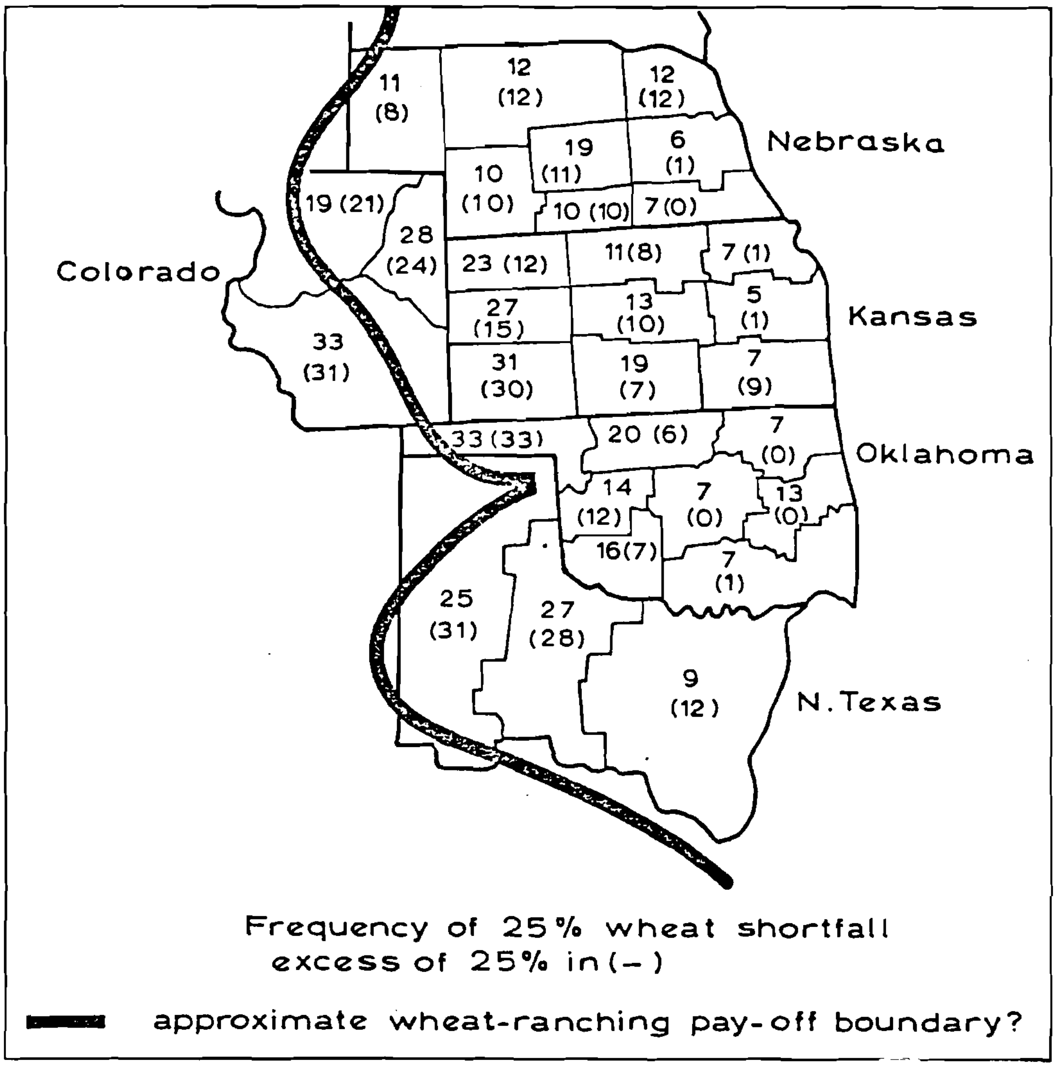


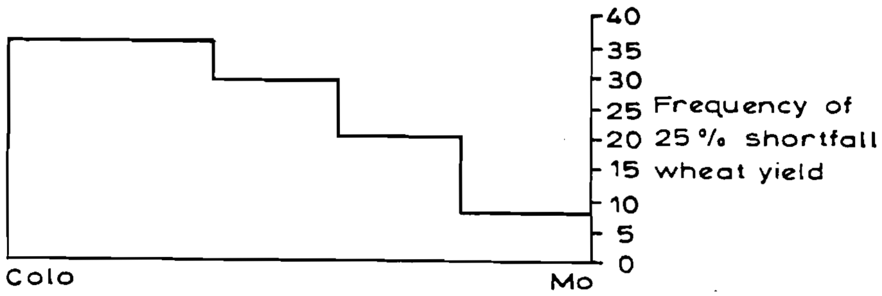
Figure 3. A 'risk surface' on the U.S. Great Plains. Frequency (in percent years) of 25% shortfall (and 25% excess in parenthesis) over 'expected' yields, of yields predicted by Michaels' (1977) winter wheat model. Data relate to 1945-75. For full explanation, see Parry (forthcoming).

Successful coping strategies might be expected to reflect real risk levels quite closely. Thus, on the Great Plains, the 'gradient' of premiums for wheat insurance mirrors our surface of climate-risk (Figure 4).

b) Canadian Prairies. It is also possible to estimate the probability of crop failure occurring as a result of a premature close to the growing season. On the Canadian Great Plains the end of the growing season is marked by the first autumn freeze, and a surface of risk due to the probability of freezing temperatures can be constructed for a network of stations based upon the estimated date of maturity of wheat (Figure 5). These data have been used to identify the effective climatic boundaries to wheat cultivation on the Prairies (Williams, 1969; Robertson, 1973).

Climate change and the secular shift of pay-off boundaries

Climatic variability can therefore be viewed as a risk surface upon which there occurs a varying probability of pay-off. Real 'boundaries' of pay-off can be mapped empirically from real enterprise boundaries; alternatively theoretical boundaries can be selected on the basis of notional critical levels of risk tolerance (e.g. a frequency of 1 in 5 failure). In either case climatic change can be evaluated as a shift of these pay-off boundaries.



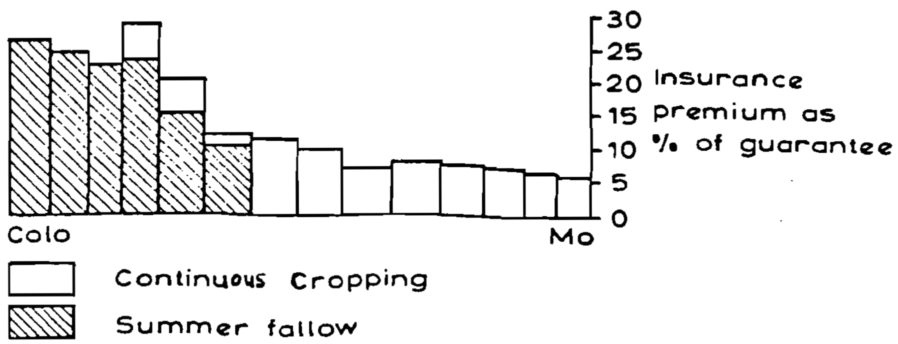


Figure 4. Cross-sections on U.S. Great Plains of frequency of 25% shortfall in wheat yield and insurance rates on wheat. Insurance data after Hewes (1979).

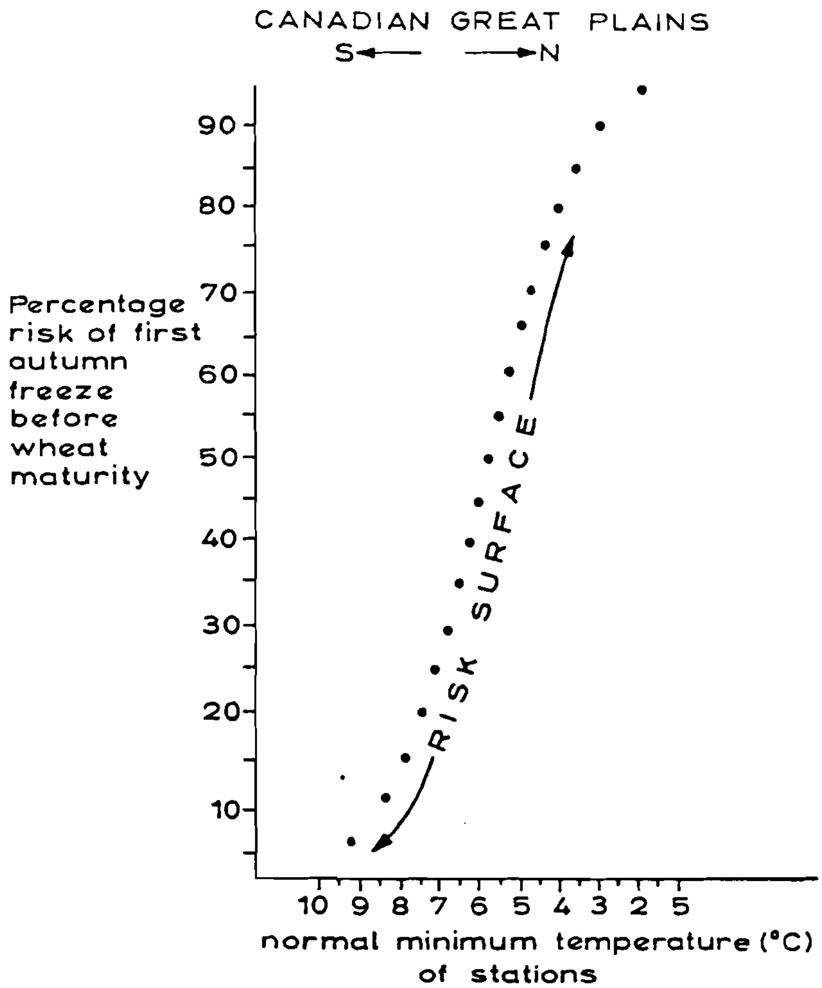
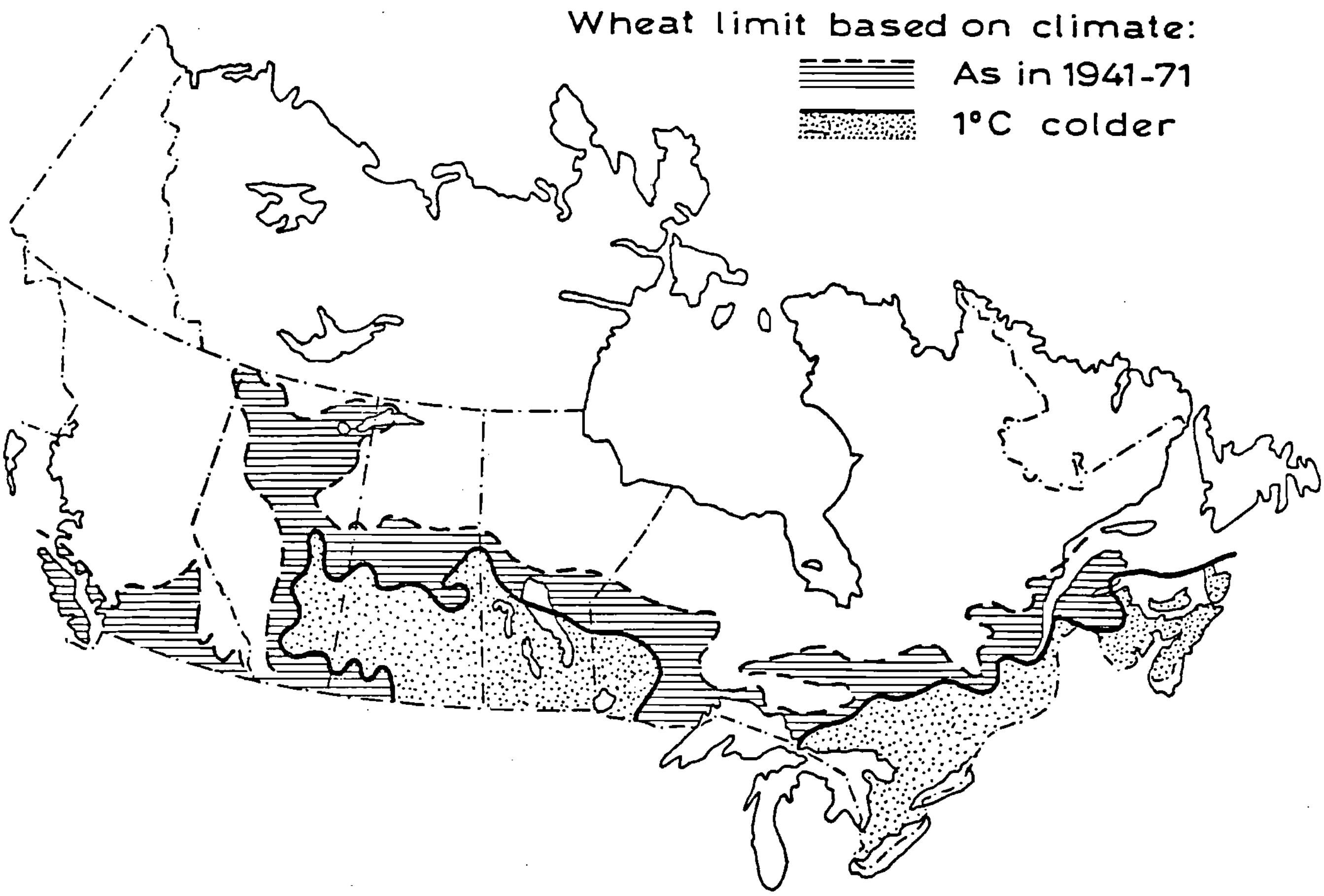


Figure 5. A 'risk surface' on the Canadian Great Plains: Risk of early freeze for different meteorological stations, characterised by given normal minimum temperatures (adapted from Robertson, 1973, after Williams, 1969).

a) Canadian Great Plains. The shift of critical isopleths has been used to determine the effect on Canadian wheat and barley production of a 1°C downturn of temperature. Biophotothermal timescale equations have been employed to estimate if and when these crops would normally reach various phenological stages at each of 1100 stations in Canada (Williams and Oakes, 1978). 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 timescale equations and brought forward the date of first fall freeze. Figure 6 illustrates the shift of isopleths bounding the wheat-maturing zone: the area suited to wheat production would be reduced by one-third. The area suited for barley would contract by only one-seventh because it extends further north and therefore is more limited



SHIFT OF WHEAT LIMIT

Figure 6 . Effect of 1°C cooling on wheat limit in Canada (after Williams and Oakes, 1978).

by terrain than by temperature. These are, of course, average estimates; no account has been taken of changes in the degree of risk.

b) U.S. Corn Belt. A second variant of the isopleth-shift approach can be illustrated by reference to work on the U.S. Corn Belt (Figure 7). Newman (1980) applied daily differences of ± 1°C to growing degree-days (GDD) for 18 stations in Indiana over a 10-year period in order to simulate the spatial shift of corn belt boundaries 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 (Kellogg and Schware, 1981), 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.

c) Northern Europe. We can also simulate shifts in the probability of harvest failure with changes in temperature alone. In northern Britain

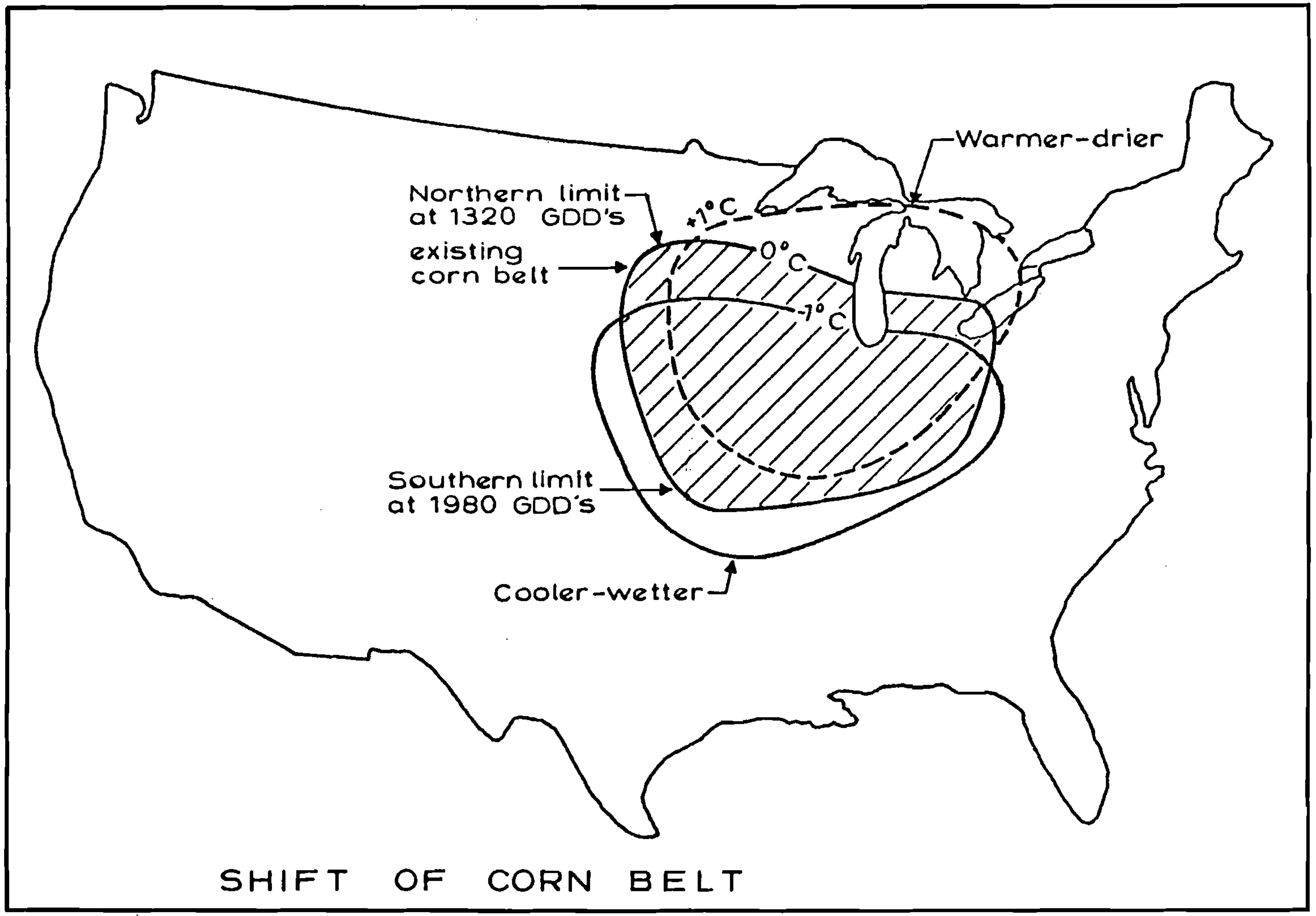


Figure 7. Simulated geographical shift in U.S. corn with temperature changes (based on frost-free growing season thermal units, GDDs) (after Newman, 1980).

in the late seventeenth century summer temperatures may have averaged about 1°C less than in the mid-sixteenth century. Such a decrease throughout the growing season would, ceteris paribus, have led to a 140-metre downward shift of the probability isopleths regarded as critical for successful cereal cropping (a failure frequency of 1 in 3.3). Across the British Isles there would, of course, have been regional variations in this shift due both to latitude and to variations in the lapse rate of temperature with elevation (Figure 8). But the evidence suggests that the agricultural response was substantial and extensive: there was widespread abandonment of marginal cropland through upland Britain (for full discussion, see Parry, 1978).

Climatic variability as the inter-annual shift of pay-off boundaries

The foregoing analysis is seriously weakened by its focus on average conditions (of yield, pay-off, etc.) and by its failure to consider that, in reality, pay-off boundaries are shifting annually and that the boundaries between, for example, different farming regions reflect a response to the perception of these inter-annual variations. We can remedy this failure by mapping the pay-off boundary for each year and analysing its inter-annual variability (and any changes in its variability). For example, we can identify, for each year, the elevation at which cereals will ripen in northern Europe (Figure 9). In some years, for example in the run of warm years 1788-1792, crops would have ripened above 550 m. In other years (e.g. 1816 and 1817) crops would, ceteris paribus, have failed even at elevations of only 180 m (1816) and 260 m (1817). In fact, there was extensive famine, bankruptcy and abandonment of marginal farmland throughout the U.K. at this time (Parry, 1978).

Given adequate data on the farming system and on climatic variability in marginal areas it is possible to construct scenarios of the impact on marginal agriculture of the weather of individual years, or 'runs' of years or of longer term climatic fluctuations. For each of these scenarios we can predict a pay-off boundary (in this case defined as crop failure) at a particular position on the gradient of the agricultural frontier. In the present example, for 'warm' years (>1700 day-degrees C) we can predict a pay-off boundary at about 400 m. For 'cool' years (<1400 day-degrees C) it would fall below 300 m. To the cereal farmer above 300 m in 'cool' years the result would be a net loss. Over both warm or cool phases we can say that the pay-off boundary will "average-out" between these elevations and that, above it, cereal farming might (again, ceteris paribus) cease.

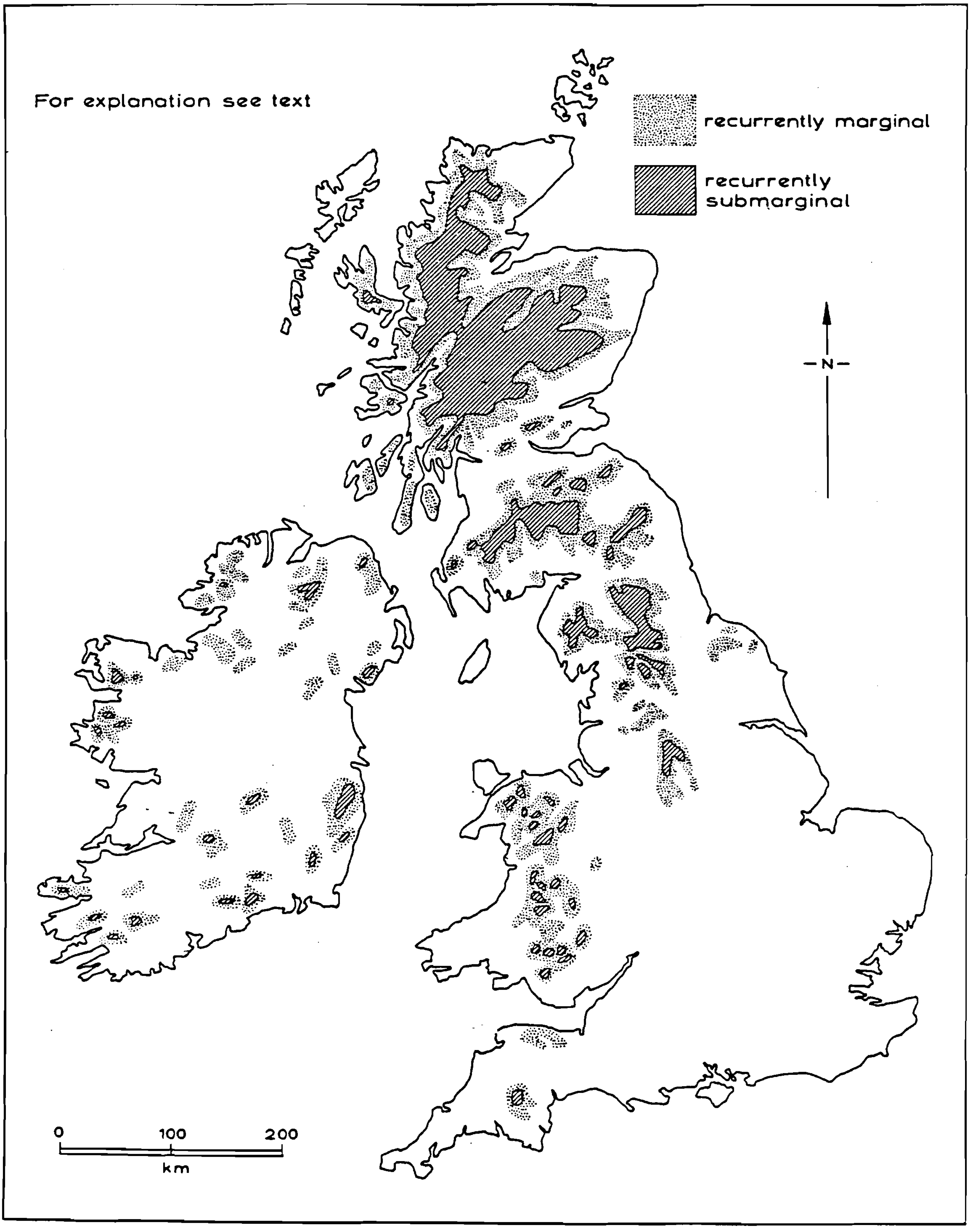


Figure 8. Recurrent marginality for oats cultivation in British Isles predicted for 1°C decrease in mean temperature (Parry, 1978).

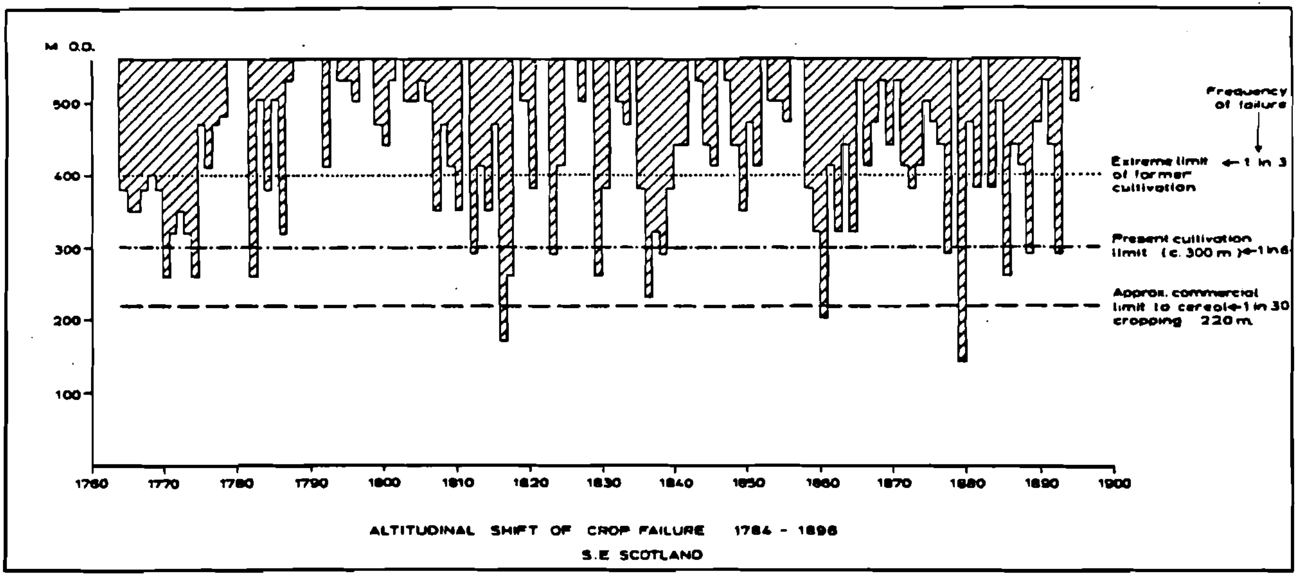


Figure 9. Simulated altitudinal shift of crop failure in southern Scotland. Failure defined as growing season with <970GDD. Data are for Edinburgh, 1764-1896. Based on provisional data and likely to be modified.

Finally, the inter-annual variability of the growing season provides us with empirical evidence of the real 'risk surface' of crop failure with elevation in northern Europe. Assuming a normal distribution of warm and cool summers we earlier proposed that the probability of crop failure increased logarithmically with elevation. This can now be confirmed, with the proviso that there is some evidence of a clustering of cool summers (Figure 10). Throughout this discussion, however, we have treated in isolation the effects of temperature and precipitation on crop growth and have thus been guilty of an over-simplification of the true complexity of crop-climate relationships. The advantage of the isopleth-shift strategy, however, is that it is sufficiently flexible to accommodate quite sophisticated crop yield simulation models.

Yield simulation modelling and the shift of pay-off boundaries

The use of marginal areas as laboratories for studying the impact of climatic variations on agriculture has been demonstrated for the examples mentioned above. One virtue of the techniques employed thus far in delimiting marginal areas, is their simplicity. It is fairly well established, for example, that an oats crop requires a basic minimum of summer warmth to ripen successfully. So, once evaluated, this may be mapped objectively for those areas where instrumental temperature data are available. Subsequent

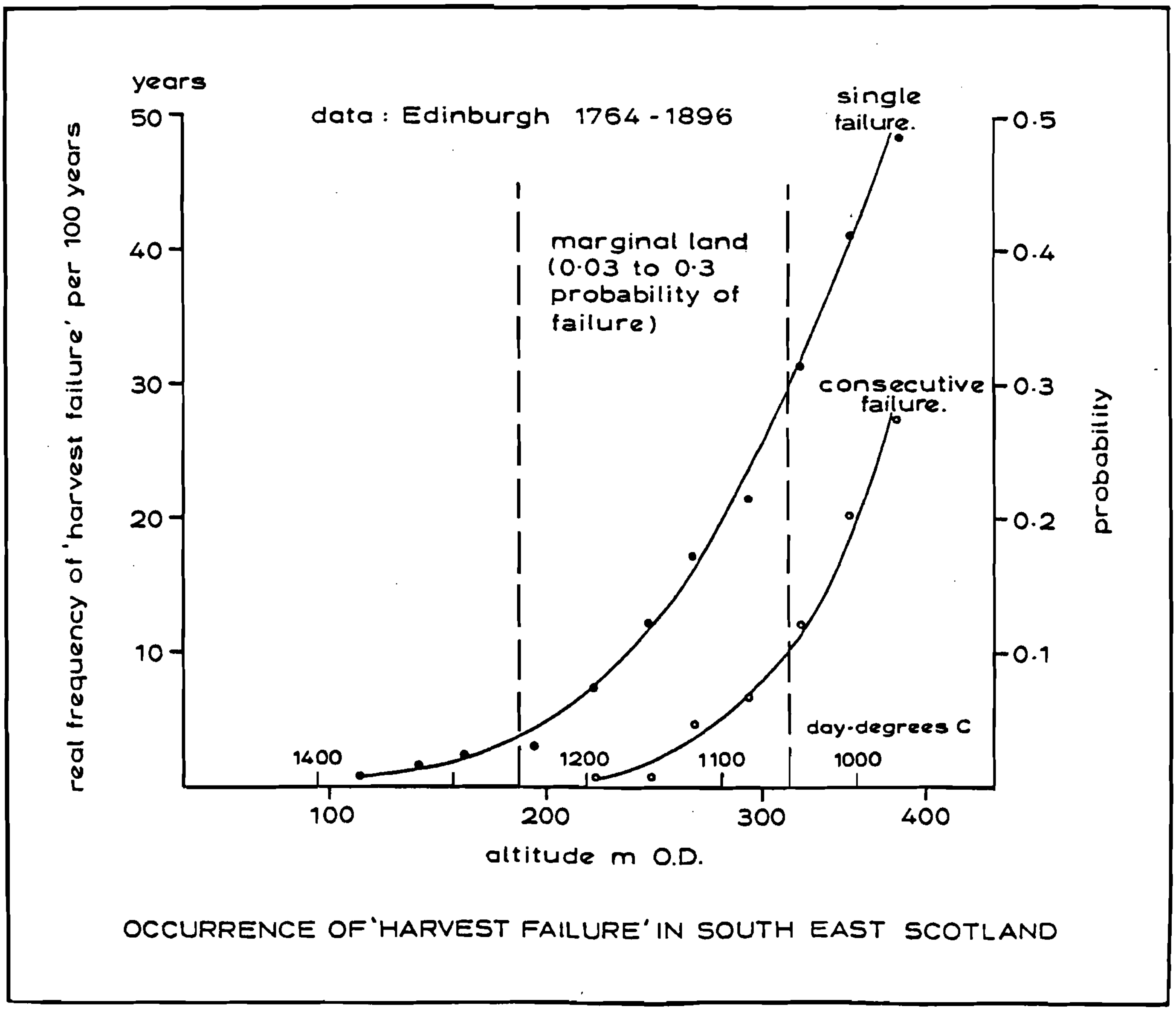


Figure 10. Real frequency of crop 'failure' in southern Scotland. Crop failure defined as growing season with <970 GDD. The crop is oats (var. Blainslie). The data are for Edinburgh, 1764-1896.

retrodiction of probable impact areas for viable oats cultivation may then be attempted and, where the data are available, these retrodictions can be tested against historical actuality. Nevertheless, for a better appreciation of climatic influences on contemporary crop production, and to assess the probable impacts of future climatic fluctuations on crop cultivation and yield, a fuller understanding of crop/climate relationships is necessary. One means of achieving this is to develop an appropriate crop yield simulation model. We shall illustrate this approach by reference to use of a model of winter wheat in England. It was developed initially by Malcolm Hough of the Ministry of Agriculture, but has undergone extensive reworking to incorporate recent field and laboratory observations.

The model simulates a crop's growth as the sum of photosynthesis and respiration processes (Figure 11). The rate at which a plant's weight increases is limited by the rate at which it can assimilate carbon dioxide from the atmosphere for reduction to carbohydrate. The rapidity of this process (photosynthesis) depends largely upon the intensity of solar radiation, the leaf area available for interception and the temperature of the plant's environment, with an additional limiting factor of water stress.

Not all the carbohydrate produced during photosynthesis contributes directly to the growth of the plant. A proportion is used up by respiration, a temperature-dependent process involving the making of new cells and maintenance of existing plant structure. Therefore, subtracting the respiration from gross photosynthesis leaves total dry matter production. Grain yield can be estimated by further subtracting the dry matter weights attributable to roots, stem and leaves using indices derived from operational and experimental observations. However, this study is restricted to consideration of total dry matter weights, hereafter referred to as 'yields'.

Simulating potential cereal yields in Northern England. a) Sowing date. An important consideration at the outset in running the model is the date at which the crop is sown. This itself may be largely determined by ambient weather e.g. an autumn soil water surplus which prevents mechanical cultivation, or an unacceptably high risk of autumn frost. The available data for sowing dates show considerable annual and locational variations. Thus, for simplicity, each model run simulates crop development commencing at 4 arbitrary sowing dates representing the observed range (late September to mid-November).

The sowing date has an important effect on the timing of leaf development during the optimum growth period, and in most cases the earlier the crop is sown, the higher is the potential dry matter yield.

b) Model operation. Simulations are executed on computer for weekly time increments and outputs include tables and graphs showing the weekly accumulation of dry matter throughout the growing season. Thus, at the

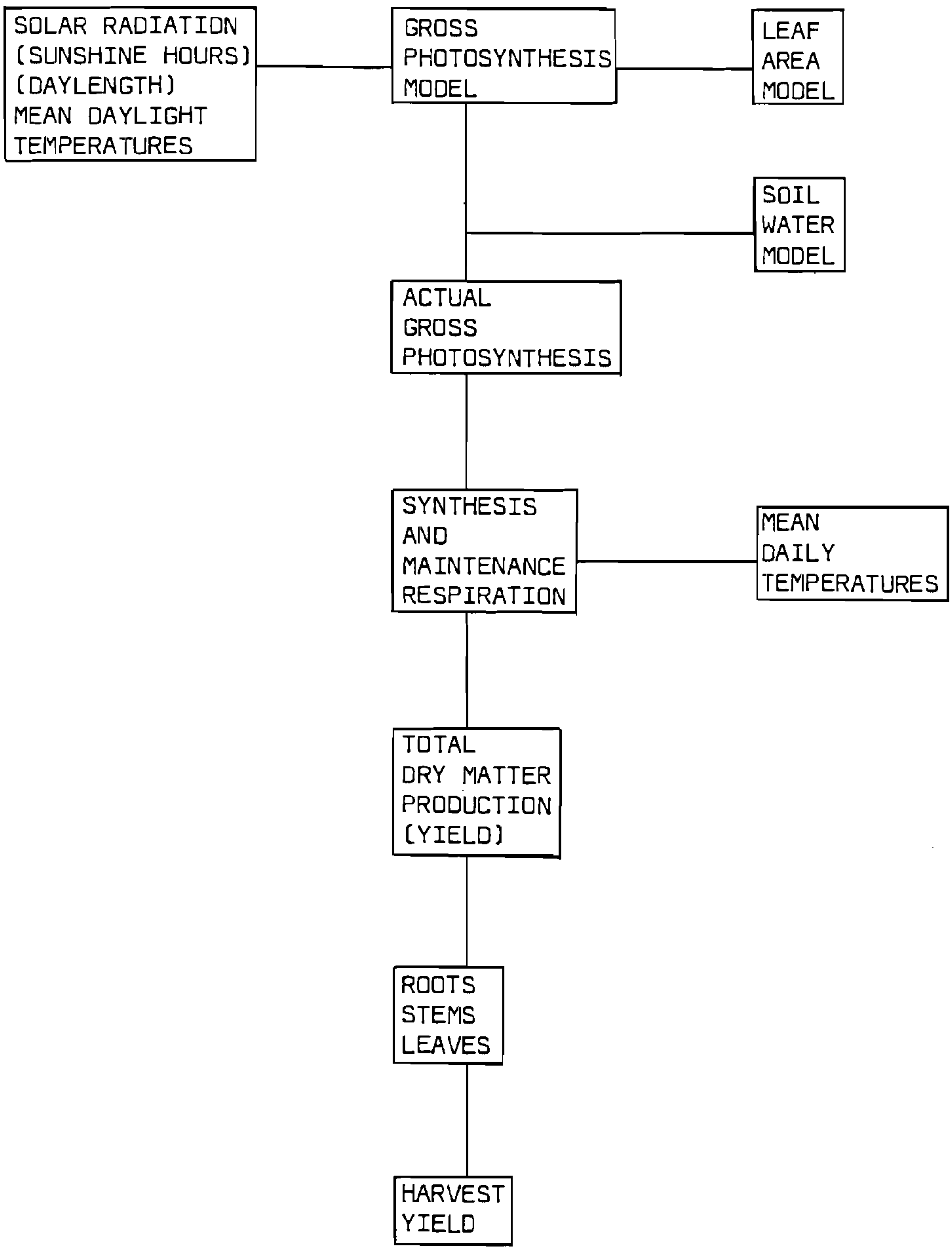


Figure 11. Flow diagram showing the major calculation steps in the model (adapted from Hough, 1981).

site of any meteorological station providing suitable data, an indication of the climatic yield potential for winter wheat may be gained.

Figure 12 offers a typical comparison between modelled yields at a lowland site (6 m) and an upland site (556 m). Two features are noteworthy. Firstly, the required growing period is considerably longer at the upland station for equivalent sowing dates (11-12 weeks). Secondly, the yields predicted for the upland station are lower than those for the lowland station (about 1 T/ha).

The sensitivity of the model may be demonstrated by comparing upland and lowland yields over two contrasting seasons. The first (Figure 13) illustrates the predictions for a cooler than average season. The development of the upland crop is considerably retarded and the yield much reduced compared with Figure 12. The latter effect is largely a result of late development and the inability of the crop to utilise fully the benefits of higher solar radiation in the summer months. This point is exemplified in Figure 14 (depicting the drought year, 1976) where the modelled yields are greater in the uplands than the lowlands. Development is more rapid at both sites with increased radiation interception, but high summer temperatures in the lowlands have actually restricted development whilst in the cooler uplands, growth conditions are close to optimum.

In these examples, the model has simulated growth conditions for a fully irrigated crop (i.e. no water stress). In most years, however, there is a marked water deficit in lowland eastern England whereas crops in an upland location are usually able to transpire at their potential rate. Thus, yields are depressed to a greater extent in the lowlands although in practice the effect is commonly offset by irrigation.

Yield thresholds, length of growing season and harvest failure. Two preconditions are now introduced which must be satisfied by the modelled crop to prevent harvest failure.

The first premise is reasonable for a majority of commercial farming operations although it may not hold for smaller scale activities. It is assumed that there is a positive relationship between level of crop yield and financial return, and that below a certain yield threshold the harvest may be considered to have failed (for whatever reason, e.g insufficient profit margin, net financial loss, net loss of seed grain, etc.).

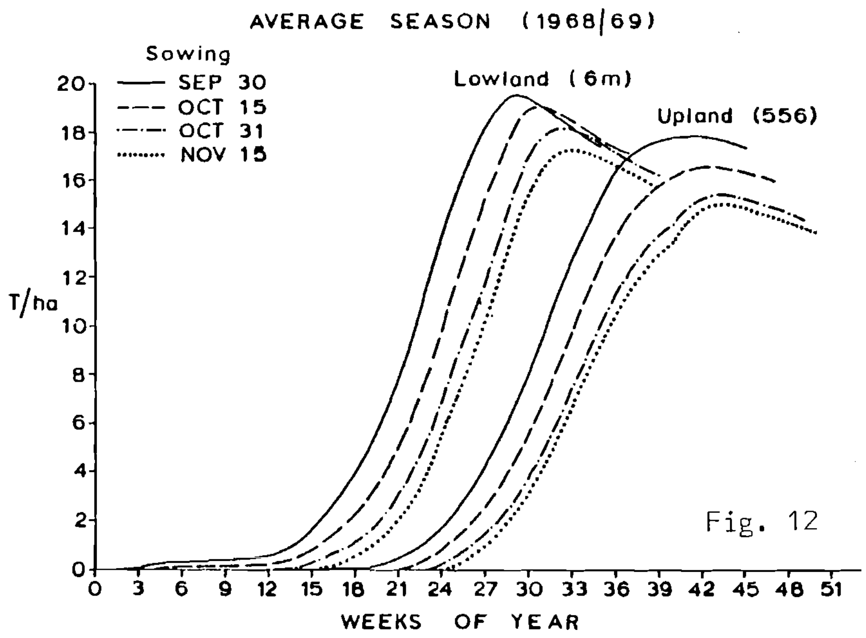


Fig. 12

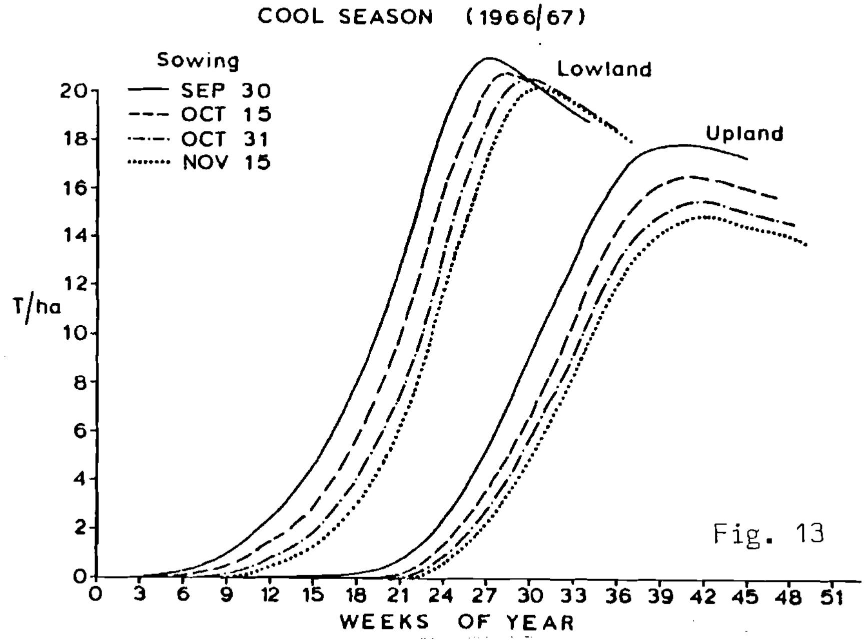


Fig. 13

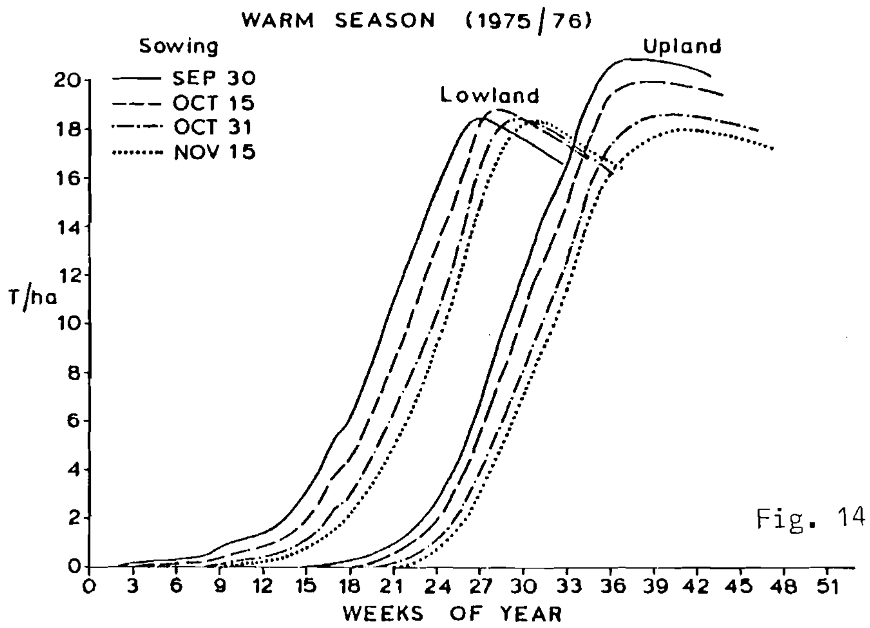


Fig. 14

Figures 12-14. Comparison of weekly dry matter accumulation of winter wheat at lowland and upland stations for average (Fig. 12), cooler than average (Fig. 13), and warmer than average (Fig. 14) conditions.

A second constraint is imposed by the length of the growing season. For a given sowing date, a cut-off date may be defined after which harvesting is considered either technically not possible or unprofitable. The very latest harvest date which is allowable is twelve months after sowing, otherwise cropping in successive years would be progressively retarded. However, other criteria are likely to restrict harvesting to an earlier date including waterlogging, moisture content of the grain, autumn frost, etc.

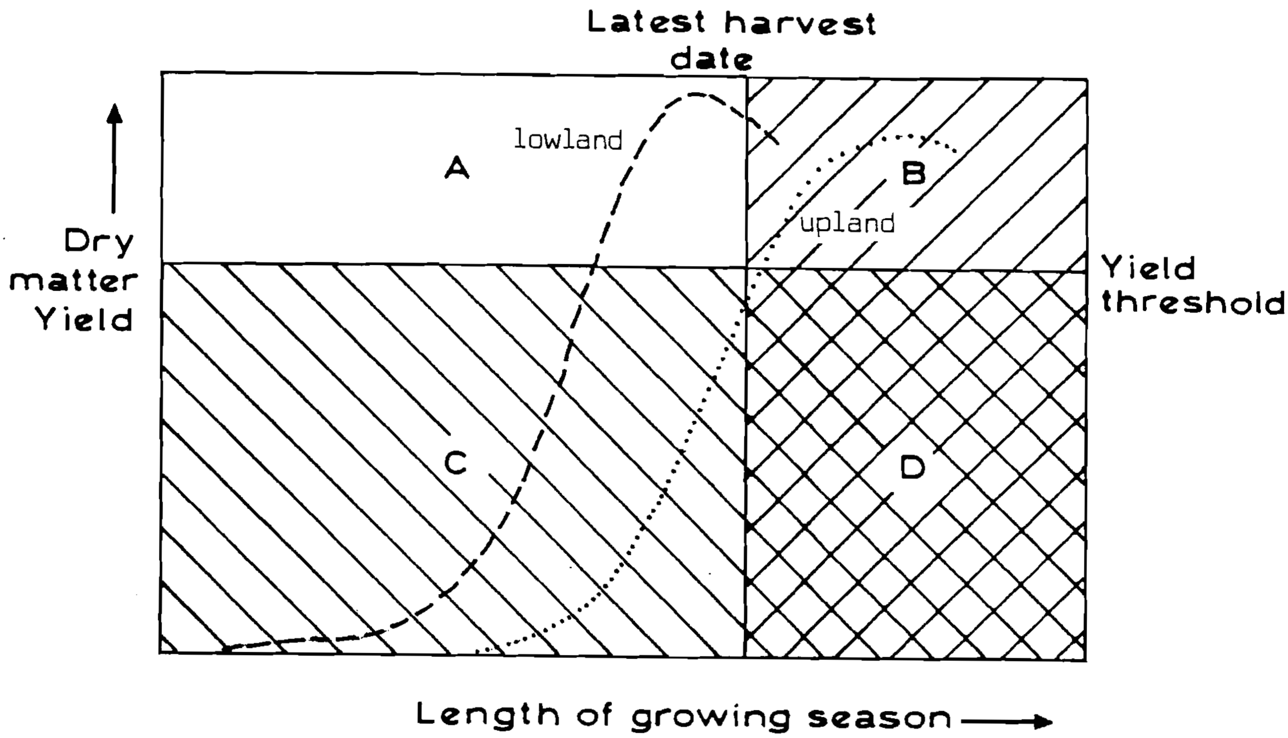
When the two constraints are imposed on an annual dry matter growth curve, four possible conditions may be defined, one resulting in a successful harvest, the remaining three describing harvest failure (Figure 15). Clearly, these are only two of the criteria which contribute to the success or failure of the harvest. Two other important factors which are not modelled but may be included in the analysis are:

(i) Waterlogging - this may prevent sowing or harvesting entirely at either end of the growing season;

(ii) Frost - the risk may be too great to allow sowing to proceed in autumn.

Frequency and probability of harvest failure. This analysis may be replicated for many stations and for different years to provide an indication of the frequency of climatically-induced harvest failure at each location. From data for a period of years the frequency can be converted to a probability of harvest failure at each station. If the station probabilities are now mapped, isopleths of equal probability may be constructed, producing a risk surface of harvest failure. A probability threshold may then be introduced, for example the probability of harvest failure above which the risk of failure is too great for cultivation to be rewarding. This may be delimited on the risk surface and represents the probability threshold during those years for which the model was operated (Figure 16).

Climatic change and the shift of isopleths. The significance of longer term climatic fluctuations (in the order of decades) can now be examined as changes in the probability of harvest failure and as spatial shifts of the isopleth of maximum acceptable risk. It would, for example, be plausible to speculate on the impact of possible future climatic changes by using the projections of certain CO_2/climate models as inputs to the cereal yield simulation model. The effects of these climatic changes on modelled yields would be described by shifts of the isopleths of probable harvest failure.



CONDITION	SUFFICIENT YIELD?	SUITABLE HARVEST DATE?	SUCCESS OR FAILURE
A	✓	✓	SUCCESS
B	✓	✗	FAILURE
C	✗	✓	FAILURE
D	✗	✗	FAILURE

Figure 15. The viability of cereal cropping. To achieve a successful harvest, maximum yield from growth curves should occur before a "latest harvest date" (vertical line) and exceed a minimum "yield threshold" (horizontal line). In 1968/9 crops at the upland station would have matured too late to be profitable.

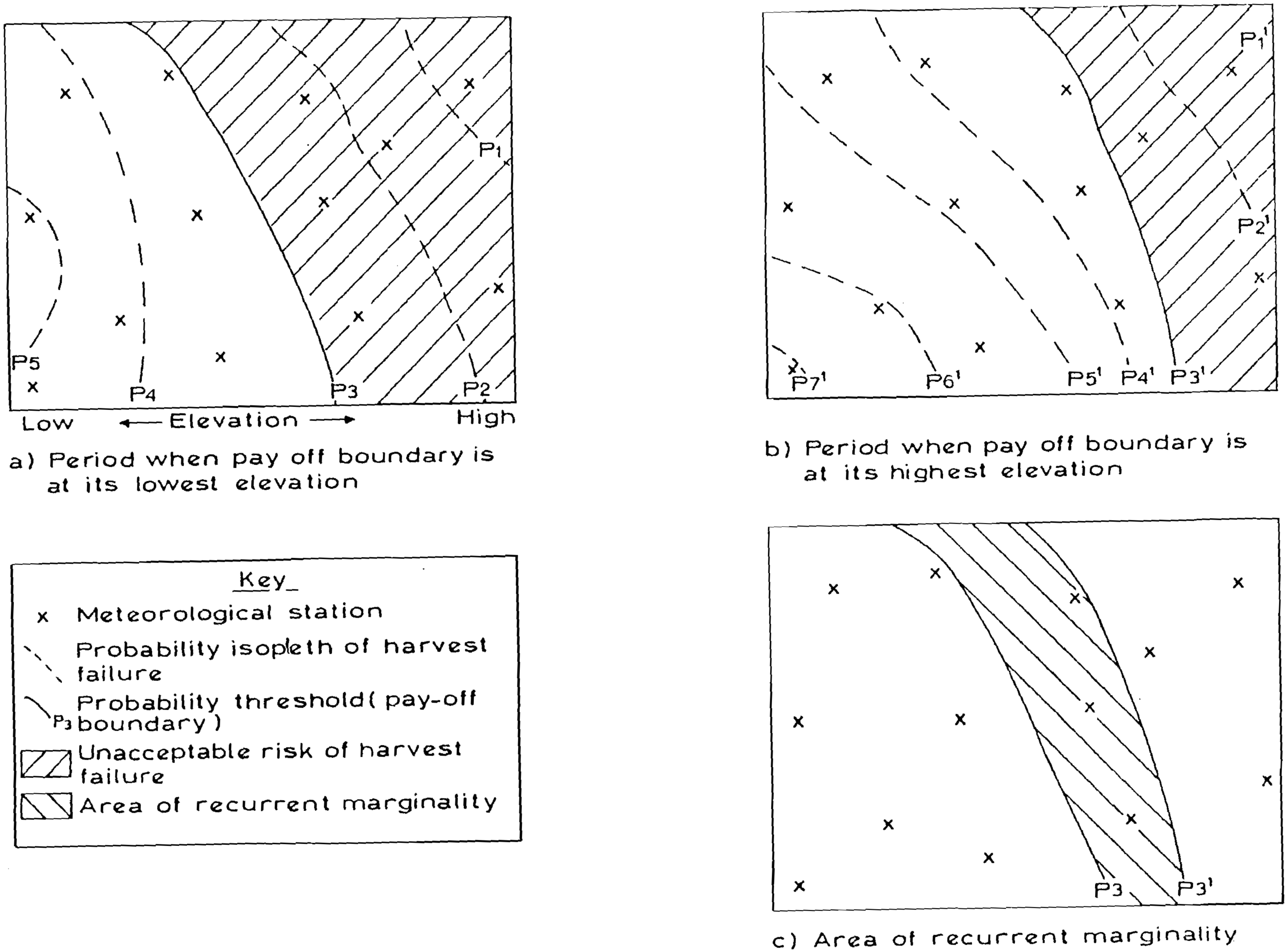


Figure 16. Idealised geographic region of low and high elevation showing differing locations of pay-off boundary in warm and cool years, and area of recurrent marginality due to variability of climate.

The areas delimited by the shifting isopleths alternate between states of unacceptable risk of harvest failure in one period to acceptable risk in another. We have termed these areas of recurring climatic impact on agriculture areas of recurrent marginality (Figure 16).

Conclusions

The strategy outlined above may be summarised as a flow diagram (Figure 17). We believe it provides a suitable framework for further studies of climatic impact assessment in marginal areas. The method of assessment requires development of models which accurately simulate the effect of weather on crop growth. Outputs from the models are designed to be compatible with measures which affect farming decisions. These vary according to farming type, economy and society, but can generally be quantified as some measure of farming risk or the likelihood of reward. The weather described by a set of meteorological data for a number of years can thus be expressed as a probability of risk or reward. 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 climate impact. Over the next two years it will be the aim of a research project at IIASA to employ this methodology and these techniques and to develop them further in order to evaluate the impact of climatic change on food production in marginal areas.

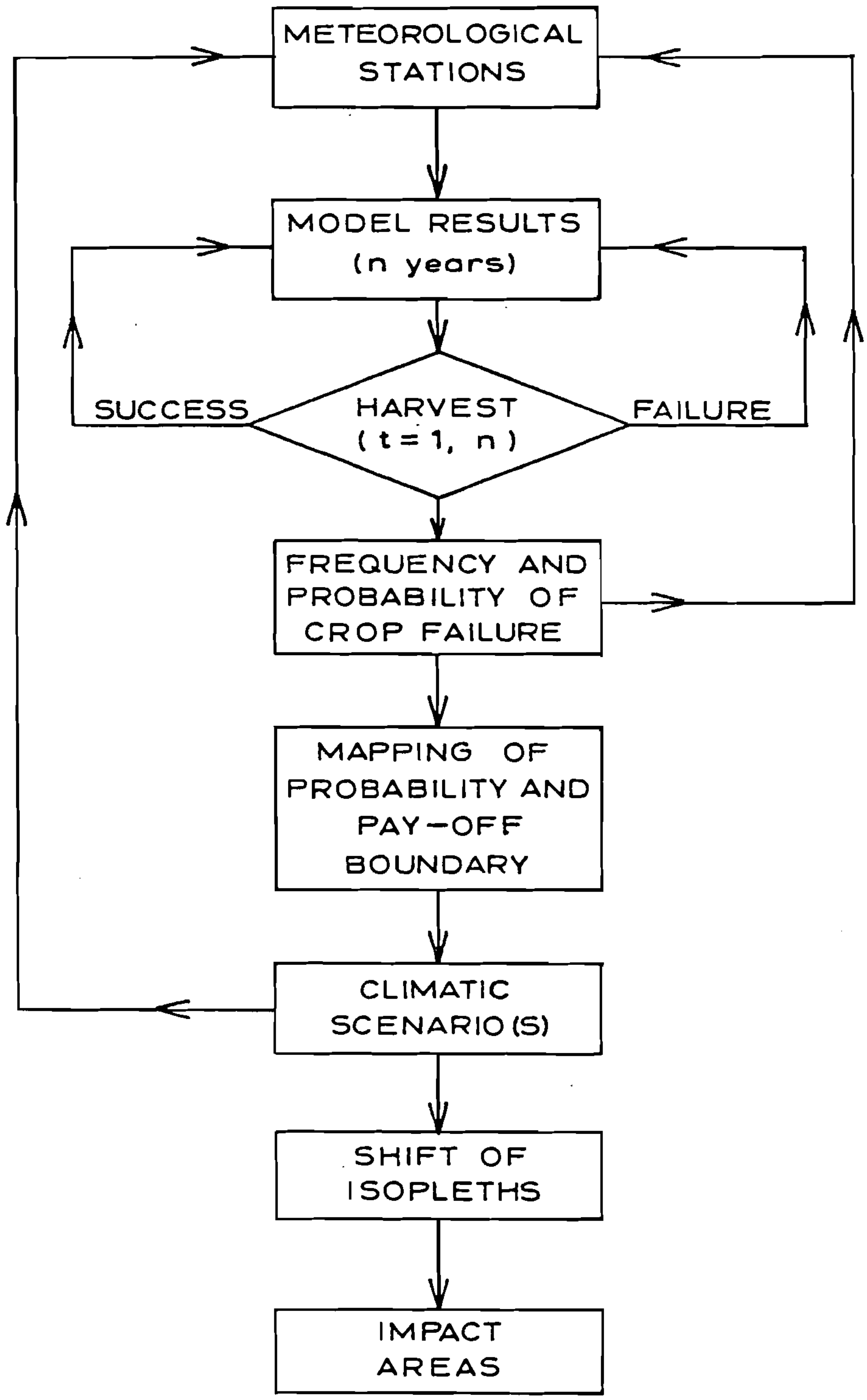


Figure 17. Steps in the identification of climate impact areas.

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