WORLD METEOROLOGICAL ORGANIZATION

COMMISSION FOR AGRICULTURAL METEOREOLOGY

CAgM Report No. 90

AGROMETEOROLOGICAL ASPECTS OF
• ORGANIC AGRICULTURE
• URBAN AGRICULTURE
• INDOOR AGRICULTURE
• PRECISION AGRICULTURE

Prepared by

N. M. Holden (Co-ordinator of the Joint Rapporteurs) and M. C. Ortiz

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TERMS OF REFERENCE FOR JOINT RAPPORTEURS ON
AGROMETEOROLOGICAL ASPECTS OF ORGANIC AGRICULTURE,
URBAN AGRICULTURE, INDOOR AGRICULTURE AND PRECISION
FARMING
(Resolution 5 CAgM – XII)

The Commission for Agricultural Meteorology,

NOTING:

(1) The recommendations of the Advisory Working Group on the establishment of working groups and appointment of rapporteurs,

(2) Increasing food production in urban and indoor environments,

CONSIDERING that more and more farmers are interested in switching to organic and precision farming,

RECOGNIZING the potential benefits that will accrue to urban dwellers and farmers from the use of these techniques,

DECIDES:

(1) To appoint Joint Rapporteurs on Agrometeorological Aspects of Organic Agriculture, Urban Agriculture, Indoor Agriculture and Precision Farming with the following terms of reference:

   (a) To define properly the mentioned fields of agricultural production;

   (b) To determine the most important agrometeorological and agroclimatological aspects of the mentioned fields of agricultural production;

   (c) To determine the most important management aspects in the mentioned fields of agricultural production that have agrometeorological and/or agroclimatological components;

   (d) To review conditions and measures to optimize agricultural production in the mentioned fields where agrometeorology can play an important role;

   (e) To submit mid-term information on the progress of activities of the joint rapporteurs and a final report to the president of the Commission not later than six months prior to the next session of the Commission;

(2) To invite the following experts to serve jointly as rapporteurs:

   Mr N. J. Bello (Nigeria);

   Mr M. Carvajal Ortiz (Ecuador);

   Mr N. Holden (Ireland);

   Mr P. Zorba (Albania);

(3) To invite Mr N. Holden (Ireland) to act as coordinator of the joint rapporteurs.
INTRODUCTION

Nicholas M. Holden, Department of Agricultural and Food Engineering,
University College Dublin, Earlsfort Terrace, Dublin 2, IRELAND

There has been a steady change in the nature of food production over the last few years. In all regions of the world there has been a shift towards organic production methods by limited numbers of producers with a view to a more earth-friendly form of production. There has also been a world-wide development of urban agriculture, particularly in regions with rapidly increasing urban populations, and difficulty in deriving maximum benefit from rural resources to feed the urban population. Likewise, the increase in indoor production has been marked over the last decade. Indoor production allows greater control over external influences, and an ability to time the harvest for maximum economic return. For those areas with large scale arable production, the introduction of precision agriculture has lead to a new way of farming, where the farmer worries about detail and variability, and tries to work more closely with the environment to achieve the best gross margin.

Each of these forms of agriculture present a new challenge to the agrometeorological community. The challenge includes understanding what the farming system is, how it works, and what interactions are influential between the farmer and the weather in determining the success of the operation. To address these issues, this report will consider four terms of reference:

(a) To define properly the mentioned fields of agricultural production.
(b) To determine the most important agrometeorological and agroclimatological aspects of the mentioned fields of agricultural production.
(c) To determine the most important management aspects in the mentioned fields of agricultural production that have agrometeorological and/or agroclimatological components.
(d) To review conditions and measures to optimise agricultural production in the mentioned fields where agrometeorology can play an important role.
CHAPTER 1

ORGANIC AGRICULTURE

(Nicholas M. Holden)

1.1 WHAT IS ORGANIC AGRICULTURE?

1.1.1 Scope

As defined by FAO (1998), organic agriculture is a method of agriculture where no synthetic fertilisers and pesticides are used. This definition is however rather open, and could be refined to include the notion that farm management is undertaken to ensure optimum soil fertility, and minimum pest problems without the use of synthetic fertilisers and pesticides. The Organic Farming Research Foundation considers organic systems to be based on developing and maintaining biological diversity, particularly in the soil. (Arising from these concepts is that of organic food, having been produced by organic farming is subject to minimal processing prior to reaching the consumer). By managing the soil-microbe-plant-animal interactions on a farm, it is theoretically, and in many cases, practically possible to produce economically viable crops. This type of farming requires a holistic approach, and the use of much "knowledge" to prevent problems before they arise, rather than managing problems as they occur. Thus it might be concluded that "agrometeorological tools" would be very useful to the organic farm manager.

The more complete definition of organic agriculture proposed for adoption by FAO/WHO is: "Organic agriculture is a holistic production management system which promotes and enhances agro-ecosystem health, including bio-diversity, biological cycles, and soil biological activity. It emphasises the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, cultural, biological and mechanical methods, as opposed to using synthetic materials, to fulfil any specific function within the system. An organic production system is designed to: (a) enhance biological diversity within the whole system; (b) increase soil biological activity; (c) maintain long-term soil fertility; (d) recycle wastes of plant and animal origin in order to return nutrients to the land, thus minimising the use of non-renewable resources; (e) rely on renewable resources in locally organised agricultural systems; (f) promote the healthy use of soil, water and air as well as minimize all forms of pollution that may result from agricultural practices; (g) handle agricultural products with emphasis on careful processing methods in order to maintain the organic integrity and vital qualities of the product at all stages; and (h) become established on any existing farm through a period of conversion, the appropriate length of which is determined by site-specific factors such as the history of the land, and type of crops and livestock to be produced."

The organic approach to farm management will be examined with respect to products, agronomy, environment and its interaction with weather. The potential for developing agrometeorological tools useful to the organic farmer will be examined, and also specific aspects of interaction between organic farmers and the agrometeorological community.

The demand for "organic" and "environmentally friendly" produce by consumers tended to be lead by environmental lobbies, and has led to some confusion as to the meaning and action of organic farming. According to Lampkin (1990) there are four major misconceptions regarding organic farming. These can be summarised as: (i) no chemicals - all food production systems rely on chemicals, organic methods avoid readily soluble chemicals and biocides, whether natural or not, (ii) substitution of organic inputs for agro-chemical (i.e. manure for fertiliser) - such a simple substitution will still lead to pollution, disease problems and no change in plant quality unless accompanied by other management changes. Slurry run-off is a problem on all farms, regardless of management philosophy, (iii)
pre-world war two methods - modern farmers cannot survive on old methods; a completely modern approach is required (and agrometeorological tools have a role to play here) and (iv) the organic farmer must have an "organic farmer lifestyle" (beards, sandals, magic, earth lovers) - this view is nonsensical, as a successful organic farmer must be an astute business man and manager with a hard practical edge in order to compete and survive.

1.1.2 History

Until the development of modern, intensive and extensive farming methods, all farming was organic. In the same way that precision farming is trying to apply the principles of small field size farming from pre-1940 to large, mechanisation-efficient fields, so organic farming is applying nutrient and biological management systems in a parallel manner; however, it cannot be regarded as a step-back in time. In much of the developed world, by the end of 1945 there was a great demand for a reliable food supply. This entailed farming systems that used mechanisation and chemicals to provide both food and a good income for farmers. By the early 1980s the global food production situation was very different. Industrialised countries were suffering from over-production, developing countries has a food shortage, and were starting to rely on crop varieties dependent on inorganic fertilisation and chemical protection (which was not economically feasible), and there was an increase in general concern for the environment and personal health. Looking at data for the UK, there were fewer than 100 organic farms in 1980, and only 700 in 1989 (Lampkin, 1990). The number, as of 1st April, 1999, was reported as 1356 farms, representing just under 300,000 ha of land (Stiftung Ökologie & Landbau, www.soel.de). Even though this number of farms only represents 1.8 % of land area, and 0.7 % of farms, it is still a substantial growth over 20 years. This growth has been driven by consumer demand; people, in Europe especially, want environmentally friendly produce, and have the disposable income to pay premium prices for it. More recently the political will has existed to address non-point source pollution in developed regions. It is increasingly likely that, along with precision agriculture, organic agriculture will provide a means for farmers to maintain production, be profitable and satisfy environmental legislation.

A potential spin-off from the consumer demand for environmentally friendly produce, and legislation penalising pollution, is that mainstream agricultural science research is likely to become more aligned with the ideas of organic farming, particularly reduced chemical inputs. This may have a significant impact in developing regions as crops should be developed that are much less reliant on high fertiliser and pesticide usage.

1.1.3 Rationale and goals

The International Federation for Organic Agricultural Movements (IFOAM) define the aims of organic farming and food processing, and it is possible to examine each of these aims in light of the climatic and meteorological environment in which a farmer is working:

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<td><em>To produce food of high nutritional quality in sufficient quantity</em></td>
<td>This is only possible using organic management where weather is not a limiting or catastrophic factor. It might be possible to manage a farm inorganically in marginal environments, but less so where unpredictability leads to increased risk. The enterprise must be matched to the climate.</td>
</tr>
<tr>
<td>To interact in a constructive and life enhancing way with all natural systems and cycles.</td>
<td>Management must &quot;take account of weather to achieve the potential of the system. It can be argued by the organic farmer that inorganic methods are only needed when land management is &quot;at odds&quot; with the natural environment, including the weather. An acceptable level of producer risk will only be found at sites which are not prone to limiting or catastrophic weather. The enterprise must be matched to the climate.</td>
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<td>To encourage and enhance biological cycles within the farming system, involving micro organisms, soil flora and fauna, plants and animals</td>
<td>Regional methods must be developed which take account of climate. A method of biological management suitable for a temperate maritime climate would not necessarily work in a region with frozen winters, or excessive heat. Management of nutrient cycling is particularly likely to be influenced by climate.</td>
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<td>To maintain and increase long-term fertility of soils</td>
<td>This goal will be at least partially dependent on water balance which depends on climate and also on inherent soil properties relating to water movement and storage.</td>
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<tr>
<td>To promote the healthy use and proper care of water, water resources and all life therein</td>
<td>Particular attention should be given to run-off rainfall events and leaching to groundwater. This aim is increasingly applicable to all methods of agricultural production.</td>
</tr>
<tr>
<td>To help in the conservation of soil and water</td>
<td>Management should aim to minimise the number of erosion events, the amount of nutrient carrying run-off, and leaching to ground water.</td>
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<td>To use, as far as is possible, renewable resources in locally organised agricultural systems</td>
<td>This will probably not be weather dependent because organic production is more likely to be weather limited than the surrounding, and supporting infrastructure</td>
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<td>To work, as far as possible, within a closed system with regard to organic matter and nutrient elements</td>
<td>This will only be possible where leaching and runoff are managed effectively. Given that nutrients are lost to the system when produce is sold, this aim requires careful analysis.</td>
</tr>
<tr>
<td>To give all livestock conditions of life which allow them to perform the basic aspects of their innate behaviour</td>
<td>The ability of land to support animals in the outdoor environment all year round is dependent of soil and weather. If this is not possible, the animal house environment will depend on local climate and shorter-term meteorological conditions</td>
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<tr>
<td>To minimise all forms of pollution that may result from agricultural practices</td>
<td>To achieve this, the farm must be managed with respect to water balance, and nutrient input. Both of these will be weather dependent because major pollution from farming is due to non-point source runoff and leaching.</td>
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To progress towards an entire organic production chain, which is both socially just and ecologically responsible

This goal will only be feasible where such a production chain does not increase farmer “risk”, i.e. where climate and meteorological extremes permit farmers to operate without the safety net of inorganic methods.

The remaining aims, listed below are not greatly influenced by climate or meteorology:

- To work, as far as possible, with materials and substances which can be reused or recycled, either on the farm or elsewhere
- To allow everyone involved in organic production and processing a quality of life conforming to the UN Human Rights Charter, to cover their basic needs and obtain an adequate return and satisfaction from their work, including a safe working environment
- To consider the wider social and ecological impact of the farming system
- To produce non-food products from renewable resources, which are fully biodegradable
- To encourage organic agriculture associations to function along democratic lines and the principle of division of powers

It can be seen from the list of aims, that there is a significant climate/meteorological influence that is likely to influence the success of organic farming enterprises. It is these influences that will be outlined and discussed in this report.

1.1.4 Major products produced

In this section, the major products will be considered with respect to production systems and needs. This is largely based on temperate management systems because there is more widely available information for such locations. The principle of encouraging vigour and health from day one is paramount to all organic endeavours.

**Animals**

The organic management of livestock has tended to be regarded as more difficult by potential organic farmers due to issues of health care. Modern farm management and breeds tend to require drugs, particularly antibiotics, in a manner that is not compatible with organic principles. The issues of superbugs in hospitals, antibiotic residues in food, and lack of drug efficiency in human medicine is however making organic production techniques look more attractive as long term management methods.

Organic dairying is possible and profitable. Calves born outside tend to have a greater inherent resistance to disease (Lampkin, 1990) so spring, summer and autumn calving is desirable, and subsequent management is designed to maximise health, and nutritional balance. At all times a calf will have as natural a posture and environment as possible. Management of Mastitis is achieve by careful cleaning, hosing and a diet of high quality hay. In this way it is possible to avoid all use of penicillin as a treatment.

In a beef system, the major limitation is stocking density which will be controlled by the available grass, available land for hay/silage production, and the amount of fixed-cost that can be allocated to animal housing or shelter. In general, a suckler system is the easiest to manage organically because the mother cow acts as the supervisor to the calf, and there is little difficulty in managing food supply via this route.

Sheep are used in mixed low-land farming systems, particularly as a complement to dairy herds. The sheep flock will graze out weeds and keep pasture healthy, have a positive effect on re-seeded pasture development, and extend forage crop grazing into the winter without excessive poaching effects. Homeopathic health management of sheep is regarded as
being viable provided the flock has good nutrition, particularly for pregnant ewes. For high-land sheep, protection against extreme weather is important in order to ensure a vigorous immune system, thus requiring little drug intervention.

Organic pig units tend to be free range unless the weather is poor, then covered housing is preferred, again to preserve good health. Pig production will tend to be part of a mixed enterprise with land supporting pigs for 1-2 years and crops for 2 years, which gives the soil time to recover structure. To ensure a good flavour of meat from free-range pigs, a mixed forage diet is necessary.

Finally, organic egg production must be considered. Free-range methods are the norm, therefore the flock will require land area. A flock of 1000 birds will need about 2 ha, and will consume grain from 7 ha in a year. If the flock is maintained in large housing, it can be organic in theory, but this goes against the humane farming practice for which smaller housing units of 100-200 birds are required. The manure from the birds has to be used in the nutrient management of the farm, and plays its part in ensuring all year grass availability for the flock. In order to make hens economically viable, they have to be of the highest quality, otherwise the cost of organically produced feed make the return unacceptable.

In summary, animal production must be carefully balanced so that numbers can be supported using as much on-farm feed as possible. Excessive numbers mean health problems and less easily regulated nutrition. This has to be balanced against the need for a good profit for the effort, i.e. acceptable level of risk.

Forage

Grass production is of importance to both organic livestock farmers, and arable farmers. For arable farmers, grass/clover ley represents a period when fertility recovery takes place, while for the animal producer, it is the fundamental means of production.

In conventional agriculture, mono-, or limited species swards reliant of mineral fertilisers have been common for the last 20+ years. In an organic system, the sward must contain legumes which will fix nitrogen, and a range of species and varieties of both grass and herbs (e.g. ryegrass, cocksfoot, timothy, chicory, ribgrass, clover, fescue). The herbs are included to increase the mineral content of the sward, and to help manage mineral mobility in the soil. The organic farmer has similar techniques available for managing a sward as a conventional farmer, but is restricted in the range of nutrient input sources available. In general, because of the restrictions imposed by the organic philosophy, it is necessary for farmers with livestock to: carefully maintain a balanced sward, ensure ample re-growth after grazing, keep stocking rates balanced to manure input, and to maintain an all year availability of food for the livestock (which is essential for good health). The cost of the grazing system employed (in terms of hardware and labour) will dictate how successful the farm is at a given enterprise. The geographical location, soil and weather will be major limiting factors in dictating outcome, and the system that can be supported.

At all times, maximum use of sunlight by the sward should be maintained. The presence of "weed" species tends not to be such a problem as it is with conventionally managed swards. In order to manage weeds it is necessary to understand why they are there, and to treat the cause, not the effect. Thus rushes indicate poor drainage; increase drainage and the rushes will not thrive! Thistles can be topped regularly to reduce spreading, and docks, once ingrown can only be controlled by summer cultivation. Docks can be prevented by not over manuring, avoiding poaching of the soil, and removing seed sources.

Fodder crops can be grown as alternative feed supply, but never in successive years to ensure that pest or disease infestations do not occur. They also provide a means of grass weed control. Detail of rotations does not need to be considered here (see Lampkin,
but the climate and seasonal patterns will dictate exactly what crop can be grown where, and when.

**Cereals**

Cereals are popular organic crops because they can attract premium prices. It is necessary to use high-quality, disease resistant varieties to be successful, and if cultivation and rotation take account of prevention of weed proliferation, then yield will be high. Sometimes mixing a resistant variety with a higher yielding variety will ensure a good return. It is usual to have no more that two years of cereals, possibly three if nitrogen levels remain high enough. Winter oats provide a good third year crop because they thrive in lower nitrogen and quickly exclude light to prevent weed growth. Clover will be used in the rotation to ensure nitrogen levels are maintained in the soil, either under-sown with a cereal crop, or in a grass sward.

**Vegetables**

Beans are often grown for two reasons, to help control weeds, and to fix nitrogen, but can result in there being weeds the following year. By planting with a close row spacing the resulting canopy keeps the weeds down. Vegetables are often grown at the field scale after a grass/ley when fertility is high, and they can yield a high return compared to other crops. The disadvantage of growing vegetables is the intensive management and time input required. Careful timing and extra labour are often needed, which with weather uncertainty can increase risk for the organic farmer. The large number of machine passes means soil damage can be a problem, thus access has to be limited to suitable times. With an organic system this raises serious problems if the weather is poor at critical times. A crop like potato is possibly good for a farmer because it can be mechanised, thus not requiring so much labour, and if only included in rotation once every four or more years, pest problems are less of an issue. Regrettably there is no organic solution to potato blight, so pests are a big problem for the farmer, and a significant risk. In general vegetables are only suitable where soils are medium to light.

1.1.5 **Geographical occurrence**

The information presented in this section is based on a survey commissioned by Ökowelt GmbH, and was undertaken by Stiftung Ökologie & Landbau (SÖL, Foundation Ecology & Agri-culture, Bad Dürkheim, Germany) in conjunction with IFOAM (Willer & Yussefi, 2000).

Organic agriculture is to be found all over the world. In terms of land area under organic management, the top ten countries are: Australia (1 736 000 ha), Canada (1 000 000 ha), USA (900 000 ha), Italy (788 070 ha), Germany (416 318 ha), Argentina (380 000 ha), United Kingdom (291 538 ha), Austria (287 900 ha), Spain (269 465 ha) and France (234 800 ha). In terms of world regions, organic agriculture is most important in Europe where over 3 000 000 ha of farm land are under licensed organic production. While organic agriculture has a foothold on all continents, it is particularly lacking in Asia and Africa, which is probably a reflection of the lack of concern with production philosophy rather than the lack of farmers actually using organic techniques to some extent. With the exception of a few European countries, percentage land area under organic production currently stands at less than 1 %, and predominantly less than 0.5 %. (N.B. the survey of Willer & Yassefi, 2000, is based on 1997 figures).

On a continental basis, the extent and perception of organic agriculture can be evaluated thus:

Africa - agro-chemical use is low, but organic produce is not sold separately or marketed as such. Organic agriculture is of interest because there is a perception that (Walaga, 2000) (i) western methods have not worked well, (ii) chemicals are out of reach of many farmers, (iii) organic methods use indigenous knowledge, (iv) international markets will pay a premium for
organic produce. It can be expected that organic farming will expend in Africa, therefore accessible information tools to support farmers and integrate modern techniques with indigenous knowledge will be useful in the future.

Asia - There is certified organic production in most Asian countries, but very little because there is relatively little current local demand for such produce. Japan is a major organic market (International Trade Centre, 1999), and the market in India is growing. There is however a promising future with China, India, the Philippines, Thailand and Malaysia all planning to introduce legislation governing organic production.

Europe - Organic farming is developing rapidly in Europe, with land area under organic production growing exponentially. There is an increasing demand locally for organic produce, and it is predicted than by 2005 organic produce will have a 5-10 % market share (Scandurra, 2000).

North America - Canada, USA and Mexico are all exporters of organic produce (ITC, 1999) and both Canada and USA have growing domestic markets. Legislation, particularly in the USA is currently problematic because draft laws are not compliant with international standards, while in Mexico there is no legal enforcement. It is expected that demand for organic produce will grow by 20 % per year in the USA (Harding, 2000) therefore importing will be necessary in the near future because supply will not match demand.

South (including Central) America - There is a presence of organic farming in most South American countries, but it is only significant in Argentina and Brazil. Most organic production is for export because there is little local demand. Organic farming is of particular importance in Argentina where there is state support available, and other countries are looking to implement legislation to provide a basis for exporting produce (Lernoud, 2000) to regions with strict controls like Japan and the EU.

Oceania - In terms of land area, Australia has the largest area under organic production of any country in the world. This is a reflection of demand in Japan, the EU and North America for organic produce, particularly horticultural crops. Apart from Australia and New Zealand, the smaller states make little contribution.

1.2 THE PRODUCTION CYCLE OF ORGANIC AGRICULTURE

Organic farming has to pay close attention to soil management practices with a view towards increasing organic matter content and biological activity, and meeting mineral deficiency of soils. In general this can be achieved by careful crop rotation and strip cropping to ensure changing seasonal demand on individual nutrients and rooting at different depths. Supporting practices include use of rock dust, manure, crop residue, food production residue, and compost to manage nutrient balance, and careful tillage to maintain aeration and water status in the soil.

1.2.1 Crop selection

Crop selection is based on suitability for the rotation to ensure nutrient management, soil quality and pest and diseases are not a problem. Crop suitability for position in rotation (derived from Lampkin, 1990) is based on the influence of the crop on various aspects of the soil condition and pest/disease/weed control:
Suitability of crops for soil types (derived from Lampkin, 1990) depends on the varieties and not just the species, but for any crop, the wetter the area, the lighter the soil needed to achieve top yield:
**Lightest sands:** Rye, lupin, carrot, kidney vetch

**Light soils:** Barley, beet, potato, peas, short leys, horticultural crops

**Light chalks:** As above except potatoes, but including sainfoin, lucerne and trefoil

**Medium loam:** Almost anything

**Heavy clay:** Wheat, oats, beans, mangolds, leys, permanent grass

**Fens and silts:** Wheat, potato, beet, horticultural crops, root crops (for seed), buckwheat

**Acid soils:** Oats, rye, potato

**Wetter area:** Oats, turnip, longer leys

Generalised rules for developing crop rotation combinations based on crop suitability (derived from Lampkin, 1990) can be created, and more complete software packages for the task have been programmed as management tools (Zander and Kächele, 1999) but these are site specific and integrate climate by their empirical design. Climate/soil driven systems may be the next development stage:

Crops 1:

<table>
<thead>
<tr>
<th>Crop 2:</th>
<th>wheat</th>
<th>winter barley</th>
<th>spring barley</th>
<th>rye</th>
<th>maize</th>
<th>peas</th>
<th>field beans</th>
<th>Lucerne/red clover</th>
<th>ley</th>
<th>potato</th>
<th>early potato</th>
<th>beets</th>
<th>brassica</th>
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<tr>
<td>winter wheat</td>
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<td>winter rye</td>
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1.2.2 Land preparation

Soil cultivation for organic agriculture is theoretically little different to that of any conventional agriculture. The aims are the same: to produce a structure (tilth) optimal for the germination and development of the intended crop; to control water content and aeration; to manage weeds and pests; to bury residues; to incorporate manure and to alleviate compaction. Given that the organic farmer is not in a good position to compensate for poor cultivation it is essential that this stage be correctly performed. The availability of suitable weather (not too wet or dry) is important, thus the forecast of coming weather over a 5-7 day period is very important.

Ploughing is the primary cultivation; if this is performed when the soil is too wet compression is likely to occur which can lead to plough-pans and poor drainage. Ploughing
should be moderated to ensure that sufficient biological activity remains to maintain structure, particularly with respect to the earthworm population. If weed management is not required then a less disruptive cultivator may prove a better alternative, but this would not be appropriate for silty soil, which may be prone to slaking and capping. Minimum cultivation and direct drilling techniques are not very suitable for organic farming where burning straw or using herbicides is not permitted. Residues however can help protect soil from erosion, so cultivation without ploughing may be suitable (i.e. in parts of the world or at specific sites where rainfall erosion is a big problem). The method of soil preparation used should be suited to the crop, the soil type and the local climate. Calcareous soils with a loamy texture are probably good candidates for reduced cultivation techniques. Non-calcareous soils will tend to need more frequent ploughing to maintain structure. If the lack of weed control resulting from reduced cultivation results in the need for more harrowing later in the season, the extra machine time (and possible soil damage as a result) may offset the cultivation gain. Furthermore, ploughing can help reduce the impact of disease by breaking life-cycle.

Occasional deep cultivation will always be necessary but should only be performed when the soil is in ideal condition (not too wet or dry), and between times, what ever method maintains the best soil structure, and allows access to the land in every year should be followed. A deep loosening (without turning) helps maintain the balance of organic matter and reduces compaction. This can then be followed by a shallow rotary cultivation to create a good seedbed. A one-pass method (Figure 1) may be a good solution, that is a combination of deep share (for general loosening), a shallow rotovator and a final crumber for surface finishing. This approach however result in soils that have very poor surface structure that will be prone to capping if the operation is followed by heavy rain. A hard crust could develop if a cap is subject to severe drying after formation.

A further consideration is energy consumption, which is not a defined element of organic agriculture, but should be considered within the "spirit of intent". A one-pass system will generally consume much more energy than a moderate plough and minimal harrowing system. It would seem appropriate that the least energy should be consumed to achieve the desired result.

1.2.3 Sowing

Given that the seed bed produced by tillage is correctly matched to the crop being sown, then there are no aspects of sowing specific to organic farming. Standard technology can be used to ensure the correct plant density. It is particularly important that gaps and low density areas do not develop so that weeds have less chance to exploit available light.

1.2.4 Management

After nutrient and soil management, the control of pests and disease is vital to the success of an organic enterprise. Unlike the conventional farmer, an organic farmer has less options to use "preventative" spraying before a problem even exists, or even in response to known adverse conditions (such as potato blight warning periods). There is however a case for
using warnings, alerts and alarms in order to get the most from available plant protection systems.

The primary strategy in controlling pests and diseases is prevention. Organic farmers maintain healthy soils (fertilising and building soil organic matter through the use of cover crops, compost, and biologically based soil amendments) which produce healthy plants, which in turn are better able to resist pests and diseases. A diverse population of soil organisms, insects, birds, and small mammals will act to keep pest problems in check. When pest populations get out of balance, growers can implement a variety of strategies such as the use of insect predators, mating disruption, traps, and barriers. As a last resort, botanical or other “non-toxic” pesticides may be applied under restricted conditions. Weeds are controlled through increased cultivation, as well as through cover crops, mulches, flame weeding, crop rotation and similar management methods. The common strategies used for pest and disease management include:

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manipulation of crop rotations</td>
<td>To minimise survival of crop-specific pests (in the form of, for example, insect eggs, fungi) which can infest the next crop unless the life-cycle of the pest is broken</td>
</tr>
<tr>
<td>Strip cropping</td>
<td>By breaking up the field into a number of different habitats, some of which are hopefully not beneficial to supporting species specific pests, the spreading of pests over large areas is moderated</td>
</tr>
<tr>
<td>Manipulation of pH or water content of the soil (in irrigated areas)</td>
<td>By making the soil environment unsuitable for elements of the pest or disease life-cycle, thus protecting the farm from long-term problems</td>
</tr>
<tr>
<td>Manipulation of planting dates</td>
<td>Plant at a time optimal for crop growth and vigour and least beneficial for the pest</td>
</tr>
<tr>
<td>Adjustment of seeding rates</td>
<td>To achieve an optimal rate in order to maximise crop health, to crowd out weeds or avoid insects, and to create ideal growing environments without pressure for nutrient resources (it should be noted that this is also a principle of precision farming)</td>
</tr>
<tr>
<td>Use of appropriate plant varieties and livestock breeds</td>
<td>There is little room for a mis-match between the farm’s environment and the produce being grown. The best variety or breed for local conditions will ensure healthy produce less susceptible to problems</td>
</tr>
<tr>
<td>Stock culling to enhance genetic resistance</td>
<td>If very severe problems might occur, accelerating natural selection is an option, but this might be regarded as going against the intent of organic farming</td>
</tr>
<tr>
<td>Careful stock buying</td>
<td>With due care and attention, plant stock or animals brought on to the farm should not import diseases onto the farm</td>
</tr>
<tr>
<td>Limiting field size</td>
<td>This makes weed management by livestock easier and more effective</td>
</tr>
<tr>
<td>Biological control methods</td>
<td>Intended to encourage natural enemies of pests by providing habitat (for example hedges) or by breeding and releasing them in areas where they are required. The latter approach might be regarded as going against the principle of organic farming, if not the licensing conditions</td>
</tr>
</tbody>
</table>
**Trapping insects**
- Using lures such as pheromones to physically remove the pest

**Biological pesticides**
- (e.g. derris dust, pyrethrum, rotenone) of which the active ingredient is short-lasting, and which may be produced locally

For weed management, both climate and meteorological information should be of significant value to the organic producer. Plant competition models may have a value for assessing the relative importance of intervention with respect to gross margins. Weed control in an organic farming system can be achieved principally by the following practices, all weather dependent to some degree:

- **Rotation design**
  - Crop types
  - Field access timing and soil damage

- **Manure management**
  - Storage and spreading requirements
  - Field access and pollution risk

- **Fertilisation**
  - Field access and pollution risk

- **Varieties**
  - Growth and development rates through the year

- **Seed rates**
  - Light competition effects

- **Green manure**
  - Production and utilisation

- **Pre-seeding Cultivation**
  - Seasonal access
  - Field access and soil damage

- **Sowing date**
  - Recent weather influences field access timing

- **Mechanical intervention**
  - Recent weather influences field access timing and soil damage

Pest and disease management for organic agriculture could probably benefit from tools that will predict the likelihood of needing intervention due to pest/disease positive conditions, but should also consider when conditions are likely to be right for natural predators or improved crop vigour. The main controls for pest and disease recommended are all weather dependent to some degree:

- **Balanced rotation**
  - Crop types
  - Field access timing and soil damage

- **Diverse population ecology**
  - Species competition

- **Companion planting**
  - Plant compatibility and control effect

- **Varieties**
  - Growth and development rates through the year

- **Seed rates**
  - Light competition effects

- **Balanced nutrient supply**
  - Storage and spreading requirements

- **Sowing date**
  - Field access and pollution risk

- **Mechanical intervention**
  - Recent weather influences field access timing

- **Harvest**
  - Field access timing and soil damage

1.2.5 Harvest

Harvest technology can be any method appropriate to the crop provided it does not interfere with the principles of organic production. Given the premium value of the organic crop, it is clearly preferable to harvest under ideal conditions for quality and subsequent storage, thus the organic farmer might wish to be well informed of the weather at this crucial time of the year.

1.2.6 Post-harvest considerations

As with the production stage, it is not possible to use chemical preservatives once a crop has been harvested. It is possible to add sand, clay, wood ash, plant residues or oils to a harvest store in order to protect the crop by repelling insects. Smoke can also be used. The
organic farmer is however not restricted, compared with the conventional farmer in how product is stored and transported in terms of high-tech silos and stores, provided they do not rely on inorganic additives. In areas with a low-tech agriculture system and local market strategies, a process such as fermentation will destroy insect eggs, aid preservation and can enhance nutritional value.

1.2.7 Animal production

Organic meat, dairy products, and eggs are produced from animals which are fed organic feed and allowed free range and outdoor access. Organic livestock and poultry are only exposed to antibiotics, hormones, or medications in the event of illness. They are given wormers and similar products that have been derived from natural sources, but diseases and parasites are controlled through preventative measures only.

Livestock are, for many organic farmers, the central pivot of their crop rotation. This is because the livestock are the means of moving nutrients around the farm in the form of non-human consumable feed and manure. It is assumed that animal health is directly related to welfare. There are three basic principles of organic livestock husbandry: highest possible welfare standards; feeding based on physiology using largely on farm produce and drug use should be minimal and not routine. The latter is sustainable with good welfare, good housing and good feeding. Two major aspects of stock handling need considering, these are housing and the clean grazing system. Well designed animal housing is part of any farming system using livestock, and using the criteria of Kiley-Worthington (1986) it is possible to assess any system. Organic farming is particularly concerned with permitting normal species behaviour and access to grazing in season. Ethologically advanced housing has been of less general concern to the wider agricultural community than developing environmental control systems over the last few years. Organic livestock housing particularly needs to account for local climate and meteorological extremes in order to provide acceptable shelter. Clean grazing is designed to break the life-cycle of parasites in order to maintain good animal health. The season is split into two parts based on the fact that larvae die off and cannot infect in spring/early summer, and that sheep and cattle are usually not effected by the same spices of nematode. Clean pasture is clear of contaminants, safe pasture has only low levels and acceptable pasture is safe except under exceptional circumstances. As the availability of the classes of pasture varies with available land (and has to be considered for the following year) and the weather being encountered, the possible approaches to clean grazing are: preventative (clean pasture available in early season), evasive (clean and safe pasture only available later in the season) and dilution (where no clean pasture exists and a low rate of susceptible stock are mixed with a high rate of older more resistant animals). It is generally thought that clean grazing systems only work well in dryer areas, and that in wetter locations parasites survive longer thus making the system inoperable.

1.3 AGRO-ENVIRONMENTAL INFLUENCES ON PRODUCTION BY ORGANIC AGRICULTURE

1.3.1 Climatic requirements and limitations

From a purely theoretical point-of-view there is no climatic limitation to the practice of organic agriculture. Organic production pre-dates modern methods, and farmers today are using such techniques all over the world. In a commercial environment where organic production is pitted against current conventional systems there is however a strong likelihood that climate will limit gross margin potential in those cases where production of a particular crop is near the limit biologically. Evaluation of agroclimatic potential for each region is a necessary precursor to a consideration of agrometeorological requirements. For any region where organic production is to be developed there should be a clear understanding of the agroclimatology, particularly the frequency of occurrence of weather conditions that typically result in situations that require chemical intervention in conventional systems (e.g. how frequently do conditions
conducive to the spread of pests and diseases occur?), and also an estimation of the workable soil days available. A number of specific climate related issues can be addressed:

### Animals

| Outdoor days | Organic systems require a reasonable duration of outdoor days in order for the animals to have a life similar to that which may be expected naturally. A greater number of outdoor days also facilitates management of feed |
| Calving conditions | Calving should occur outdoors therefore the risk of extreme weather (particularly wet and cold) should not be excessive |
| Grass production | In conjunction with the grass growth rates (which will be climate influenced), the available land area will dictate the number of animals that can be supported. The grass production will dictate both the direct feed and the silage production. The climate and soil will dictate the number of animals that can be supported with reasonable risk |
| Clean pasture | Clean pasture systems are a first line control of pests, particularly parasites. The grass growth and land area will dictate how much clean pasture is available over the course of the year and the climate will perhaps dictate the duration of parasite survival |
| Soil damage | The soil type, in conjunction with the weather/climate will dictate the type and magnitude of potential soil damage. This factor is related to both grass growth and outdoor days |
| Weed control | Sheep are a leading method of weed control, and thus accessibility, health and soil damage must be considered and all are limited by climate |
| Free range hens | Sufficient land area, access and feed supply are required. In the case of feed supply the quality of feed available on the range has to be matched by varying quality of grain fed to ensure no wastage. The stock density will be limited by the land available to grow supplemental feed or its regional availability both of which will be climate limited |

### Crops

| Climate limits | Individual crops have to be assessed to ensure they will function as a suitable economic product given climate limitations and to ensure balanced crop rotations are possible for nutrient management |
| Sowing date | The best crops have to be chosen, but a total cover should be maintained because gaps allow weeds to develop, thus the start of the cycle for each crop has to be linked |
| - Temperature | The progression through growth stages will be largely influenced by temperature and seasonal patterns |
| - Degree days | By matching variety to growth potential the crop health and cover can be carefully maintained at an optimum level |
| - Photoperiod | There must be sufficient light available for the crop to be the dominant species in the field and for it to develop optimally |
**Water requirement**

Climate will dictate whether there is enough water available naturally, and the regional demand where irrigation will be necessary. In addition side effects of irrigation will be partially influenced by climate.

**Timing of harvest**

The combination of the above factors will dictate harvest date. The crops chosen should offer little risk based on the regional climate. The risk of poor harvest due to the onset of bad weather should also be considered.

**Fodder crops**

Can be grown but never back-to-back because of infestation risks

**Cereals**

Have to offer a high return so conditions must be *ideal*, not adequate as might be possible with conventional production

**Swards**

Mixed species and legumes offer the best soil/pest/weed management options

**Tillage**

**Access**

Climate, along with soil will dictate when access to a field is possible: trafficable days

**Method**

Likelihood of soil damage and the need for weed control will influence the choice of method. Soil workability will be crucial

**Number of passes**

Soil damage and weed control and frequency/duration of access will be weather controlled

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Agroclimate can be viewed as a three scale hierarchy (c.f. Petr, 1991) for the purposes of planning an organic farming enterprise. At the largest scale there is the *macroclimate* which is a reflection of geographical factors over a wide area (millions of square kilometres) and the interaction of topography with air masses. There are various approaches to climate classification (Barry and Chorley, 1982). The classification by Strahler (1969) divides the world into region by latitude and air mass influences with further sub-division based on a dominant feature (Figure 2). The typical climatic characteristics of each of these regions (Figure 2) should provide the primary information for both the suitability of a farm product-enterprise/system, but also an indication of whether it is likely to be weather limited by pest, disease, access or operational timing problems by integrating the climate data with knowledge of limiting factors (e.g. by the use of models to aid decision support).
At the next scale, the mesoclimate can be considered. Covering a scale of tens of kilometres, the mesoclimate will be reflected in the farmers view of the weather experienced in the region. Local topography and surface features will be of influence here, with hills or small mountains, large forest areas, extensive plains and the like causing a distinct effect. Typically a country will be found in one, or perhaps two macroclimate zones, but within its borders there will be many mesoclimates (highlands, central plains, coastal regions). In Ireland Keane (1998) defined 20 agroclimatic regions based on the representativeness of the synoptic observation network. The question that still has to be asked about these regions is if weather information on a meso-scale regional basis is appropriate for organic farming? The answer is probably yes. It is at the mesoclimate scale that specific calculations can be made to define agroclimatic regions. Petr (1991) defined three climatic regions (based on temperature sums) for what was the country of Czechoslovakia, but within each of these agroclimatic regions further subdivisions were defined either on the basis of local temperatures or the hydrothermic coefficient:

\[ HTC = \frac{R}{0.1TS_{10}} \]

where HTC = hydrothermic coefficient, R = rainfall sum (mm) ad TS_{10} = degree days above 10\(^\circ\)C (Figure 3). A similar analysis can be undertaken for any defined characteristic in order to develop organic production specific agroclimatologies.
There is a clear need for the development of regional agroclimateologies targeted at organic production. These should take account of the three major issues facing the organic farmer: access to the land, pest and disease management and timing of operations. The formulation of these climatologies can be based on known formula for factors such as (examples of pest and disease only, not complete list of all possibilities):

- **Potato blight risk**
  - Smith Periods (Smith, 1956)
  - Negative prognoses and spray interval – NegFry (Ullrich and Schröder, 1966; Fry *et al.*, 1983)

  Requires regional analysis of daily data for at least 15-30 years – cannot be derived directly from climate data.

- **Cereal disease**
  - Polley periods to predict mildew (Polley and Smith, 1973)
  - King periods for *Septoria tritici* (King, 1972)

  Relationships not fully understood, but may provide an indication of the risk that may occur and the necessary effort to overcome it.

- **Crop pests**
  - *Rhopalosiphum padi* population and rainfall/temperature (A’Brook, 1981)

  Relationship is empirical and does not hold true in all regions. A generalised approach is required for successful application.

- **Frascioliasis–liver fluke**
  - Ollerenshaw index (Ollerenshaw, 1966)

  This is a predictive index that can be based directly on climate data because it uses monthly data. Can also be used as a year-by-year tool for risk assessment.

A statistical analysis of the potential frequency of occurrence of pests and diseases could be based on archival data for a county. The division of data into regional mesoclimates is however essential because down-scaling daily data that may be required for some of the calculations will not be appropriate.
The small scale microclimate is a reflection of weather at the local scale. Within the area of landholding of an individual farmer there may be a number of distinct microclimates (such as cold hollows, warm sun exposed slopes, dry elevated locations, shelter belts...). The individual farmer should be aware of these different areas and how they influence farm management. An area of the farm that has prolonged wet soils may not be suitable for use in a clean pasture system, or a slightly more humid area of a field may promote disease development that may subsequently spread. Farmers converting from conventional production may tend to think on a field-by-field basis. For organic production, due to the limitation on chemicals, smaller-scale detail may well be of significance and definition of farm microclimates may be of benefit in this regard.

The agroclimatological requirements of organic agriculture can be summarised in terms of the basic questions that the farmer must ask when considering adopting organic methods such as:

- Which crop will grow within the climate region?
- Will the climate permit suitable growth over the whole season?
- Are there likely to be land access problems during tillage and planting?
- Are there likely to be operation timing problems, particularly at harvest?
- Are local climatic conditions conducive to particular pests, weeds or diseases?
- Will it be possible to implement a soil nutrient management scheme with the crops that can be grown in the area?
- Are there areas of the farm that need particular attention?

On a national basis, it would make a lot of sense to have agroclimatologies on-hand that will address planning and development questions and to facilitate decision making at both the national (macroclimate) and regional (mesoclimatology) scale. An analysis of potential changes in climate would also be of benefit to ensure that expertise built up over many years will remain applicable into the future.

**Requirements for organic agriculture:**

- National macro agroclimatologies (organic production specific)
- National mesoclimatologies (organic production specific)

### 1.3.2 Meteorological requirements and limitations

While climate can tell us something of the likely risks associated with a developing agricultural enterprise, it is meteorological conditions over a specific, much shorter time period (the synoptic situation) that dictate the actual success or failure of the enterprise. The occurrence of specific meteorological events, and perhaps more importantly the combination of events, dictates how a crop develops, whether a farmer can access land at a particular instant, and whether pest and diseases will flourish. For production agriculture in general there have been a large number of models developed, many of which rely on meteorological data as driving inputs (see for instance Orlandini (1998) for a survey of crop disease models). With respect to specific modelling tasks the various meteorological variables measured can be related to specific effects. Examples from plant pathology are (Orlandini, 1998):
The value of meteorological inputs to models are of most relevance to organic farmers when they can be used for predictive purposes. A conventional farmer may use measured weather data to establish that disease conditions have occurred and therefore apply treatments such as spray before symptoms are visible in the crop. This will probably ensure maximum productivity and therefore better gross returns. Such an approach is fundamentally flawed for the organic farmer who cannot use chemical intervention in such a manner. The organic farmer needs forecast data – ideally over periods of (i) a year – to assess the best protection strategies, the timing of operations and for financial management – this is of course an ideal that will never be supplied; (ii) a season – the selection of varieties and the types of operations could be optimised if the farmer knew how severe a season was likely to be – again this type of forecast is unlikely to be supplied; (iii) a month – the timing of operations and management of catastrophic events would be eased with a monthly forecast – again reliable prediction is unlikely at the extreme of this time period; (iv) a week – for the timing of operations and the management of catastrophic events – this type of forecast is possible and the extension of forecast horizons is of particular interest to the organic farmer; and (v) a few days – short term management – this type of forecast is now very reliable. In reality the organic farmer should get the most from a national observation network if a very reliable 4-day forecast can be achieved, a reasonable 10-day forecast, and an indication of seasonal trend by comparison with weeks and months just past with long-term climate data. The latter will provide a framework for the relative assessment of the season’s development to date.

The mesoclimatological data for a region will provide a farmer with the information required for the selection of crops and their management but it will be specific meteorological conditions that will influence the day-to-day activities for a particular year. Take for example an organic farmer producing premium product, small changes in planting date and access times can be critical. Figure 4 shows a yield map that reveals the effect of planting date on the yield at harvest (Langkilde, 1999). It can be seen that on the left of the field a strip of yield was much greater and had been sown earlier. The moderate yield strip was sown 4 days later and the low yield area (most of the field) was sown 5 days after the first access to the field. The farmer noted that the field looked uniform, but concluded from these data that he should invest in wide tyres for his machines so that spring access was never limited.
The provision of suitable resolution data as both observations and forecasts would be of major benefit to organic producers to form part of a service for assisting with risk management. The various types of meteorological observation will be briefly reviewed, some comment made on their utility for organic farmers and an assessment of the required density of observation/prediction will be made.

### Meteorological observations and forecasts

**Radiation (solar radiation, sunshine hours, cloud cover)**

**Observations:**
- Total solar radiation
- Photosynthetically active radiation
- Cloud cover
- Hours of bright sunshine

**Radiation data are most important to the organic farmer for:**
- Plant growth prediction (plant development through the various growth stages)
- Animal comfort and health (cold or heat stress)
- Irrigation requirements (driving force of the hydrological cycle, particularly important for evaporation prediction)

Incoming solar radiation is the driving force behind all agriculture. Agriculture can be regarded as the commercial exploitation of the conversion of solar energy by photosynthesis and the storage of energy as crop biomass. From the point-of-view of the organic farmer crop light-use efficiency, competition for light and the ability to withstand extremes or limits of radiation will dictate crop selection, weed management strategies and the success of rotations. The example in Figure 4 shows how a short period of bad weather (which limited field access) could influence yield at harvest, but the season long accumulation of radiation will also effect the type of crop that can be grown (a climate driven decision) and how profitable a given crop is in a given year. The occurrence of bright sunshine hour and cloud cover can provide a farmer with an indication of radiation inputs where direct measurement is not possible (Villalpando et al., undated):

\[
R_g = \left[ a + b \left( \frac{n}{N} \right) \right] R_o
\]

Where \( R_g \) is the predicted incoming radiation, \( n/N \) is the proportion of sunshine, \( R_o \) is the theoretical radiation at the top of the atmosphere and \( a \) and \( b \) are regression coefficients.

In the context of the density of observations required, radiation does not vary greatly over short distances. Data for Ireland suggest that site specific radiation data are not really required (Figure 5) because there is little meso-scale spatial variability. There is some variability in sunshine (due to cloud mainly), but in practise a farmer could use local observation

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**Figure 4:** Variation in spring barley yield due to planting date (Langkilde, 1999)
if necessary to make use of this information in a more informed manner. The accuracy of the data required will be dictated by the intended use. With decision support tools the sensitivity of the models involved will be important, but for informed decision making ±10% is probably acceptable. Daily data are desirable for model input. Information about radiation is perhaps most useful when used in a modelling context. Relatively simple models such as the Irish grass growth model (Brereton et al., 1996) are driven by radiation inputs and are used to inform farmers of expected yields to improve short term management.

Figure 5: Left – Deviation of incoming solar radiation over Ireland from the national average at any given time (derived by a score and ranking system). Right – Bright sunshine hours for Birr (central Ireland) between 1951 and 1980.

Temperature (degree days, maxima, minima, frost, cold stress)

**Observations:**

- Air temperature
- Soil temperature

**Temperature data are most important to the organic farmer for:**

- Plant growth (plant development through the various growth stages)
- Plant quality (frost damage, wilting)
- Harvest date prediction
- Animal comfort and health (cold or heat stress)
- Irrigation requirements

The concept of the growing degree day is of great potential use to the organic farmer. It is based on the assumption that plant growth is directly related to temperature, and that each crop has a temperature limit below which it will not grow. A simple approach to this is to assume a fixed temperature over which a crop grows and a minimum accumulation of growing days to reach harvest stage (see Table 4 in Villalpando et al., undated). A more sophisticated approach is to assign different base temperatures depending on the growth stage or the season (Keane, 1986; Brereton, Carton and O’Keefe, 1985). Even if the base temperature used is not perfect, the concept of growing degree days will provide the farmer with a quantitative basis for comparison of a particular growing season with other years, and climatological data. Over a 15 year period in the west of Ireland grass growth varied from 255 to 329 days. The ability to predict harvest times, quality and yield is of particular importance for the organic farmer who has to decide how much time and energy to invest in a particular standing crop. Similar concepts can be used for the management of fruits in terms of chilling and frost days.
The health of livestock can be significantly influenced by temperature. Outdoor birthing is supposed to be as natural as possible. This means cold stress to new born animals is a particular issue in temperate latitudes. Cold stress prediction requires temperature forecasts on a farm scale (10 km²). Currently observations are not made at such a fine resolution but there are methods available that could be of particular interest to the organic farmer (Dozeman et al., 2001). Using known relationships between temperature and altitude, location (based on regional relationships such as the clear coastal influence in Ireland) and aspect it should be possible for farmers to enhance the value of mesoscale forecasts. Temperature is of particular importance for the day-to-day comfort and health of free range poultry and pigs.

The role of temperature in prediction of water requirements and drying rates is also important to producing quality crops. The organic farmer has a responsibility to interact with natural cycles in a responsible way (see section 3.1) and therefore irrigation and forced drying have to be viewed carefully.

**Water balance (precipitation, evaporation, relative humidity)**

**Observations:**
- Precipitation
- Evaporation (calculated?)
- Evapotranspiration (calculated?)
- Soil water content

**Important with respect to:**
- Land management and access (tillage, weeding, harvest)
- Plant growth (plant development through the various growth stages)
- Irrigation requirements
- Pest and disease infestation
- Animal health

The seasonality, frequency, intensity, type and total precipitation are of great concern to organic agriculture. At the outset, the water balance, influenced by soil type, precipitation inputs, and outputs (drainage and evaporation) will dictate land access and management. It is particularly important for organic agriculture that land access is possible a critical times of the year (sowing and harvest, but also for mechanical weed management). The interaction of precipitation with soil type will partially dictate land suitability classes in an area. A forewarning of extreme events at critical times of the year would be most useful with respect to: tillage, planting dates; weeding dates (and strategy); cutting dates; drying requirements; irrigation scheduling; and water use efficiency management techniques. A statistical analysis of climatic rainfall pattern would be of benefit to the organic farmer, in order to evaluate available meteorological data, particularly in critical years. If we look at three rainfall stations in Ireland we can find the probability of a day being a rainday, and the probability that a rainday is rainday following a previous rainday, and 2,3,…,n raindays:

<table>
<thead>
<tr>
<th>Malin Head [north]</th>
<th>Birr [centre]</th>
<th>Roches Point [south]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of rainday:</td>
<td>65 %</td>
<td>57 %</td>
</tr>
<tr>
<td>Probability of following a rainday:</td>
<td>51 %</td>
<td>41 %</td>
</tr>
<tr>
<td>Predictive equation (up to 7 days):</td>
<td>$y = 62.476 e^{-0.2046x}$</td>
<td>$y = 54.186 e^{-0.2866x}$</td>
</tr>
</tbody>
</table>

Where $y$ is the probability of the next day raining and $x$ is the number of previous raindays.

This simple exercise was undertaken based on 30 year, annual data, but could easily be applied to seasonal data. The monthly percentage raindays and the likelihood of
following a rainday with 1, 2 or 3 raindays for the example sites in Ireland (Figure 6) reveals the range of values about the seasonal mean indicated above.

Figure 6: Left – Percentage raindays, and the likelihood of raindays following 1, 2 and 3 other raindays on a monthly basis; Right – on a seasonal basis. Top – Malin Head; Middle – Birr; Bottom – Roches Point

A summary of the seasonal raindays at the three example sites:

<table>
<thead>
<tr>
<th></th>
<th>Malin Head</th>
<th>Birr</th>
<th>Roches Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>68</td>
<td>59</td>
<td>57</td>
</tr>
<tr>
<td>Spring</td>
<td>59</td>
<td>55</td>
<td>50</td>
</tr>
<tr>
<td>Summer</td>
<td>60</td>
<td>54</td>
<td>43</td>
</tr>
<tr>
<td>Autumn</td>
<td>71</td>
<td>59</td>
<td>53</td>
</tr>
</tbody>
</table>

reveals that there is a different seasonal pattern at each site, and that the number of raindays differ considerably, particularly in the autumn. Knowledge of such simple relationships would provide organic farmers with a framework for evaluation of meteorological data and forecasts, and allow short-to-medium term planning based on what is likely to happen. It should be noted that this type of approach has to be treated with caution because it cannot replace forecasting and cannot predict extreme events.
The seasonality of water input will dictate what crops can be grown in an area, and even though irrigation is acceptable practice, the management of irrigation (and sourcing of water) has to be considered carefully. Likewise, seasonality of precipitation will be of importance with respect to pest and disease infestations. If we consider King’s (1972) early attempt at predicting *Septoria tritici* infection of winter wheat we can see the importance of rainfall and the need for accurate local observation:

- Rain on two out of three days totalling at least 10 mm with rain on the first day
- Rain on three consecutive days totalling at least 5 mm
- Rain on four consecutive days
- A relative humidity of at least 90% must be recorded at 09:00 GMT on at least one day in each period.

or

- a period of sixteen hours or more commencing with rain and continuing or with a relative humidity of at least 90% with rainfall totalling at least 5 mm

Similarly a relationship between number of days with >1 mm rainfall between growth stages 37 and 59 has been related to disease incidence at growth stage 75 (Tyldesley and Thompson, 1980). Given the importance of forecasting pest and disease infestation rather than simply responding to it, empirical or mechanistic forecast techniques that provide the farmer with a management lead time are potentially very useful. There is a need to produce regional empirical relationships like the examples above in parallel with more complex mechanistic models to provide organic farmers with an array of tools to assist in predictive management.

The maintenance of crop quality, particularly with respect to pest and disease infestation is of vital importance to the organic farmer. The physical appearance of products like potatoes grown organically is one of the aspects that influence demand and value. A big, clean, unmarked tuber is valuable compared to a small, blemished tuber. The prediction of pest and disease infestation with sufficient time to plan a non-chemical intervention would be of importance. As well as the incidence of rainfall, the relative humidity will influence the survival of pathogens. The concept of the Smith Period for potato blight forecasting (Smith, 1956) – minimum temperature >10 °C and 11+ hours of >90% relative humidity – is an example of a method developed for conventional production that could have parallels for organic farmers.

The prediction of evapo(transpi)ration is of benefit because it is related to the soil water balance, crop drought stress and drying conditions. The root constant (the amount of water that can be transpired before evapotranspiration is reduced) is dependent on both the soil type (volume of water storage and potential for root distribution) and the actual crop (both type and growth stage). For the organic farmer with few intervention methods available to help stressed plants recover, the prediction and management of water stress is vital. This requires knowledge of soil (water holding capacity) and its interaction with the actual/potential evapotranspiration ratio to estimate current available soil water. Given the spatial variability in soil, it is probably better for the farmer to take responsibility for calculating available water at site specific locations on the farm based on published observations rather than a central agency trying to calculate for wide areas in a generalised manner.

Another area where rainfall and evapotranspiration interact is in the spread of animal pests such as fascioliasis caused by liver fluke. The phase of parasite life-cycle outside the host animal is largely weather dependent, and because the development is related to recent weather rather than future weather, the likelihood of disease incidence is predictable on the basis of recent meteorological observations. Empirical methods such as the Ollerenshaw Index (Ollerenshaw, 1966) provide both a summer and an over-winter prediction of the likely infestation. Using data from synoptic stations in Ireland, considerable variability in the Index values can be seen (Figure 7). The degree of small scale variability and the spatial scale at which the Ollerenshaw Index is valid are not clear. Research into the use of such a valuable predictive index is probably worthwhile.
From the above general discussion it can be concluded that the rainfall monitoring network needs to be matched by temperature, humidity and wind observations that will allow accurate calculation of evaporation (note the radiation discussion above that suggests such fine resolution observations are not required for the radiation elements except with the presence of cloud), and thus from this estimates of water stress are possible.

![Figure 7](image)

**Figure 7**: Left – the over-winter (1998/99) Ollerenshaw Index; Right – the summer Ollerenshaw (1999) Index. Points are synoptic stations. Values in brackets are the Index as a percentage of the long-term average

**Wind (speed, direction)**

**Observations:**
- Speed (10 m)
- Direction (10 m)
- Run of wind (infrequently?)

**Important with respect to:**
- Cold stress in animals
- Erosion
- Pollination
- Wind stress and plant development
- Physical plant damage
- Wind energy

The issue of cold stress in animals is probably of most concern to the organic farmer given the obligation to ensure a good quality of life for livestock. Lambs are probably most vulnerable to cold stress because their small body size means they produce little heat and have little insulation, but the performance of all animals is related to heat/cold stress. It is desirable that agreed formula for the calculation of effective environmental temperature for pigs, cattle and sheep at various growth stages be developed. The wind element in such a formula will probably be the most difficult to reliably quantify because of the effects of local scale variability, shelter belts and topography. One approach to such a problem is to define regional land types (Dozeman *et al.*, 2001) that relate to known wind speed/direction effects such as peaks, valleys, shelters using established physical relationships(Figure 8).
Similarly the effect of wind erosion has to be considered by the organic farmer who has a responsibility to preserve and enhance the value of the soil. Wind erosion ($WE$, t ha$^{-1}$) is a function of soil erodibility ($I$, t ha$^{-1}$ yr$^{-1}$), a “climate” factor ($C$), surface roughness ($K$), length of open wind blow ($L$, m) and vegetation cover ($V$, small grain equivalent kg ha$^{-1}$) (Morgan, 1986). The quantification of the factors in this relationship relies on empiricism. Just to look at the climate factor $C$, it has to take into account both the wind velocity and the soil water content. The wind velocity is expressed as a mean annual value at 9 m, while the soil water content is derived from the Thornthwaite equation such that:

$$C = \frac{v^3}{(P - E)^2}$$

$$P = E - 115 \sum_{i=1}^{12} \left( \frac{P_i}{T-10} \right)^{10/9}$$

where $v$ is the wind speed, $P$ is the mean monthly precipitation (inches); $T$ is the mean monthly temperature ($^\circ$F) and $T-10$ has a minimum value of 18.4 (Morgan, 1986). This relationship has some obvious difficulties (units aside) that need to be addressed. The first is whether the relationship can be down-scaled in space and time to use in a manner suitable to predict ongoing erosion risk for a critical farm enterprise. The second problem is whether the observation of wind speed could be made at an appropriate resolution. As with the prediction of cold stress, for a farmer to be able to determine all relevant wind speeds by observation for the land-holding is unlikely so a method of generalised spatial extrapolation is probably needed.

Other problems related to wind are not organic agriculture specific, but given the premium value of organic crops, wind damage may be very important. Forecasting of severe wind events may be of particular value for management timing. The presence of wind breaks in the form of hedges has a number of influences on the crop in the field due to modification of microclimate. The wind speed is markedly reduced (Figure 9a), the leeward evaporation rate is influenced (Figure 9b) and the crop yield is significantly effected (Figure 9c). Lampkin (1990) suggests that a lack of hedges will cause mean temperatures to be depressed.
Finally, given the goal of using renewable resources and ecologically sound management, the integration of wind energy production with organic agriculture is worthy of investigation. A general wind forecast might provide useful information on calm periods (and comparison with climate norms) and wind power forecasting would allow management with respect to variations in load demand and in the need to buy in external energy. As green energy traders emerge, the purchasing of electricity from wind farmers and selling on over the transmission system is likely to develop. To optimise this system an accurate forecast of the load profile of suppliers is needed. The combination of wind energy and organic agriculture is one worthy of closer inspection.

**Observation and forecast requirements for organic agriculture**

Given the specialist nature of organic farming and the premium value of the product, it is concluded that for organic producers to derive the maximum gain from agrometeorological research and models, site-specific decision support tools are required (rather than general regional or country scale maps with little detail related to specific topography). This would entail either linking the farmer directly to data sources suitable for operating models locally, or running models with sufficiently fine spatial resolution to permit farmers to receive results for their particular land-holding. An alternative approach is for farmers to use local, automatic weather stations. The exact instrumentation could be matched to the crop/livestock mix. For farmers, and system developers to have confidence in decision support tools using local data collection systems, the equipment must be well maintained and calibrated. For this reason it is probably better to plan for a separation of the farmer from both the meteorological data acquisition and running the models. Information and communication technology can be used to deliver site specific management information without the farmer having to needlessly delve into areas outside core competency (i.e. agricultural production).

For risk forecasting and management planning, agrometeorological models need to be integrated with numerical weather prediction at a 10-15 km grid (100-225 km²) resolution. Combining such fine-resolution risk forecasting with records from on-farm observations would however allow farmers to interpret forecasts in a more site-specific manner and therefore get the most from them. An agreed specification of regional observation and forecasting requirements for organic agriculture would serve the organic farming community well. A first draft attempt follows:
Draft specification of minimum desirable observation requirements for organic agriculture:

<table>
<thead>
<tr>
<th>Daily observation of:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Global radiation</td>
<td>1 per 10 000 km² (100 km grid)</td>
<td>5% accuracy</td>
<td></td>
</tr>
<tr>
<td>Cloud cover and sunshine hours</td>
<td>1 per 100 km² (10 km grid)</td>
<td>5% accuracy</td>
<td></td>
</tr>
<tr>
<td>PAR (could be calculated)</td>
<td>1 per 100 km² (10 km grid)</td>
<td>5% accuracy</td>
<td></td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>1 per 100 km² (10 km grid)</td>
<td>0.5 °C accuracy</td>
<td></td>
</tr>
<tr>
<td>Minimum temperature</td>
<td>1 per 100 km² (10 km grid)</td>
<td>0.5 °C accuracy</td>
<td></td>
</tr>
<tr>
<td>Average temperature</td>
<td>1 per 100 km² (10 km grid)</td>
<td>0.5 °C accuracy</td>
<td></td>
</tr>
<tr>
<td>Rainfall</td>
<td>1 per 100 km² (10 km grid)</td>
<td>0.1 mm accuracy</td>
<td></td>
</tr>
<tr>
<td>Wind speed at 10 m</td>
<td>1 per 100 km² (10 km grid)</td>
<td>0.1 m s⁻¹ accuracy</td>
<td></td>
</tr>
<tr>
<td>Wind speed at 2 m</td>
<td>1 per 100 km² (10 km grid)</td>
<td>0.1 m s⁻¹ accuracy</td>
<td></td>
</tr>
<tr>
<td>Wind direction</td>
<td>1 per 100 km² (10 km grid)</td>
<td>0.5 ° accuracy</td>
<td></td>
</tr>
<tr>
<td>Relative humidity</td>
<td>1 per 100 km² (10 km grid)</td>
<td>1% accuracy</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Daily calculation of:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Evapotranspiration</td>
<td>1 per 100 km² (10 km grid)</td>
<td>5% accuracy</td>
<td></td>
</tr>
<tr>
<td>Available water and crop stress</td>
<td>1 per 100 km² (10 km grid)</td>
<td>5% accuracy</td>
<td></td>
</tr>
</tbody>
</table>

Simple predictive mesoscale models to provide the organic farmer with warnings alerts and alarms

Draft specification of minimum forecast requirements for organic agriculture:

Farm/grid-cell (10-15 km) scale meteorological observations or NWP model predictions desirable for organic production to make forecasts:

<table>
<thead>
<tr>
<th>Forecast requirement</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>15 min observations – derive maximum, minimum and average daily values</td>
</tr>
<tr>
<td>Rainfall</td>
<td>continuous per 0.5 mm rainfall</td>
</tr>
<tr>
<td>Wind</td>
<td>speed and direction – 15 min observations – derive measures of deviation through day</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>60 min observations</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>60 min observations</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>60 min observations</td>
</tr>
<tr>
<td>Prediction of evaporation</td>
<td>60 min observations</td>
</tr>
</tbody>
</table>

Forecasts to cover nowcasts, daily, 2-day, 5-day, 7-day, 2 week, 1 month, seasonal trend information, warnings, alerts and alarms

Organic agriculture will never provide the maximum, or attainable yield for a location by comparison with conventional agriculture. The actual yield produced by organic systems is always constrained by weeds, pests, disease, access limitations and harvest limitations. Forward planning with respect to climate and the use of forecasts in conjunction with simulation modelling can be used to allow farmers to manage time and resources on a day-to-day, and month-to-month basis. One aspect of agrometeorological input to organic production that is also worthy of further consideration is the development of organic production specific alarm warnings (Keane et al., 1998). If the timing of poor weather is likely to coincide with critical operations the impact on the organic farmer will be significant, particularly if it influences post-sowing, pre-harvest management operations. The meteorological conditions of importance are (Keane et al., 1998):
Low temperature - Cold stress, frost damage, spreading risk with frozen ground
High temperature - Water stress, crop stress
Excessive rainfall - Field access, erosion, runoff, pollution, soil damage
Drought - Crop stress, erosion
Excessive winds - Crop damage, wind erosion
Low solar radiation - Weed competition

but these will have a knock-on effect on soil water excess, soil water stress, relative humidity, canopy wetness animal housing systems and pest/disease development conditions. While it is not currently clear whether there are significant differences between the warning/alert/alarm thresholds and timings for organic and conventional production in a given location, this is certainly an area worthy of further research.

1.3.3 Land suitability classification for organic agriculture

Land suitability classification is an approach to land mapping that ranks parcels of land on the basis of their suitability for a specific use. In the FAO methodology (FAO, 1976; Landon, 1984), there are three levels of description:

<table>
<thead>
<tr>
<th>Term:</th>
<th>Meaning:</th>
<th>Example:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land quality:</td>
<td>Complex attributes which affect land uses</td>
<td>Erosion resistance, yield levels,…</td>
</tr>
<tr>
<td>Land characteristic:</td>
<td>Measured/estimated property used for mapping</td>
<td>Slope, soil texture,…</td>
</tr>
<tr>
<td>Diagnostic criterion:</td>
<td>A quality or characteristic that is either a limit or a requirement of a block of land for a specific use</td>
<td></td>
</tr>
</tbody>
</table>

Defining land as suitable for organic agriculture as a specific use is of limited value except with respect to the transition period from conventional to organic production. In this case land can be mapped and classified using the FAO recommended terminology:

S1: highly suitable - No limitation (as of the current time) to full organic production
S2: moderately suitable - Normal transition period for conversion from conventional to organic production
S3: marginally suitable - Poor profitability during transition and for an extended time afterwards
N1: currently not suitable - Could be made suitable for organic production
N2: permanently not suitable - Will never be suitable for organic production

The classes could be quantified in economic terms (e.g. based on the time and cost for conversion balanced against the expected value of the semi-organic and later organic crop) and/or in practical terms (e.g. the likely difficulty encountered in the conversion process). Conversion requires that:

- A balanced rotation can be developed that will build fertility while maintaining sustainable manure management
- The blocks of land converted must be large enough to be practical
- Conversion must begin with fertility building if coming from extensive cropping
- Appropriate soil management must be possible (including promotion of biological activity)
- The risk of surface water pollution should be minimal
- Heavy metal concentrations should be within limits
At the start of the planning of a conversion process, the integration of the physical land resources with the local climate should indicate what cropping/livestock systems will be possible. The integration of an organic production agroclimatology with a physical resource survey to produce plan specific suitability maps may be a very useful step.

There are specific issues related to suitability classification that need to be briefly addressed:

**Terrain**

There is no reason, *per se*, why organic production should be limited by terrain. If terrain limits conventional production, it will also limit organic production. Perhaps a more significant issue is whether the terrain limit to profitability is more significant for organic production than conventional production. Steep slopes will make conservation of the soil resource and management of agricultural pollution more difficult for arable cropping, thus making compliance with the tenets of organic agriculture more problematic, but no specific issue arises outside the context of a land classification system:

<table>
<thead>
<tr>
<th>Limit</th>
<th>Code:</th>
<th>Explanation/examples:</th>
</tr>
</thead>
<tbody>
<tr>
<td>topography</td>
<td>(t)</td>
<td>Not organic production specific</td>
</tr>
</tbody>
</table>

**Soil**

<table>
<thead>
<tr>
<th>Limit</th>
<th>Code:</th>
<th>Explanation/examples:</th>
</tr>
</thead>
<tbody>
<tr>
<td>drainage</td>
<td>(f, w, o, p)</td>
<td>Excessive intervention to ensure sufficient field access (will relate to the climatic region and meso-scale agroclimatology). Poor infiltration and conductivity limiting access. Limits to organic manure/slurry/dirty water disposal</td>
</tr>
<tr>
<td>erosion</td>
<td>(e)</td>
<td>Soil on steep slopes, weak soil, soil subject to excessive rainfall in combination with moderate slope (will relate to the wind and precipitation climate)</td>
</tr>
<tr>
<td>strength, structure</td>
<td>(c, i)</td>
<td>Poor bearing capacity. Limits to field access. Limits to mechanical manipulation. Limits to infiltration (will relate to the precipitation climate)</td>
</tr>
<tr>
<td>texture</td>
<td>(e, g, v, h)</td>
<td>Extremes of soil texture are likely to make organic farming more problematic because of soil water management problems</td>
</tr>
<tr>
<td>depth</td>
<td>(k, b, z)</td>
<td>Shallow soil will be less suitable for multi-crop rotation systems</td>
</tr>
<tr>
<td>chemistry</td>
<td>(j, y, x, a)</td>
<td>Land requiring mineral inputs such as pH or salinity management</td>
</tr>
</tbody>
</table>

**Climate**

Climate issues relevant to land suitability classification for organic agriculture have been considered in section 3.1. With respect to the generally defined limits or land qualities, climate will have a significant influence on:
Limit: Code: Explanation/examples:
Drainage, Flooding (f) Poor surface drainage will be influenced by both the precipitation regime and its interaction with soil and topography
Available water (q) Available water is dependent on both the physical store (soil) and the meteorological factors that drive the water balance

The potential role of simulation models in the suitability classification for conversion process

According to Lampkin (1990), the main problems farmers in Western Europe have had in the conversion process are: shortage of forage, protein balance in livestock feed, yield decreases, weed control, excessive peak period workload and financial problems. Agroclimatic/meteorological models should be able to provide assistance in the conversion planning process in at least four of these areas, each of which will require a suitable spatial resolution for input data and yields data:

**Forage supply** Grass/crop/forage growth models can be used with existing climatic/historical meteorological data records to predict forage supply. (A side issue would be an evaluation of potential pollution issues with silage production and the ploughing of grass/legume leys)

**Yield** Crop growth models can be used with existing climatic/historical meteorological data records to predict the impact of the change in management

**Weed control** Weed development and competition models can be used with existing climatic/historical meteorological data records to predict the impact of the change in management

**Workload** The time requirement for each month under the new management regime can be evaluated using a range of historical weather data to predict the impact of various combinations of weather. This should provide forewarning of difficult time management situations

Similarly field-scale models should be developed using weather and soil properties to allow stocking rate planning. This will provide planning information on the likely economic return, housing requirements, storage requirements and organic waste disposal requirements. The latter needs to be integrated with a pollution control model to ensure that surface water quality is maintained in the area of the converting farm. Such impacts are currently assumed to be "good", rather than being evaluated by simulation modelling prior to conversion. A farm scale GIS implementation of forage supply, crop weed, livestock and soil/hydrology models would allow the farm to be mapped into suitably classes that could be used to assess the scale of likely problems that will be encountered during transition and afterwards.

Requirements for organic agriculture:
Field scale agrometeorological crop growth models for prediction of impact of change to organic production
Suitable resolution, meteorological/climatic input data
GIS based integration of organic production models
Weather integrated forward planning tools (advances over currently available tools)
1.4 DATA AND MODELS

Models can be used by organic farmers for three main purposes: (1) transition management, (2) risk prediction and (3) operational management. For risk and operation management data need to be site-specific and timely.

1.4.1 Data availability and resolution

The availability and resolution of meteorological data varies both in space and time. For example, in Ireland, there are only 15 synoptic weather stations (1/5629 km², 75 km separation), 80 climatological stations (1/1055 km², 33km separation) and rain gauges at about 1/100 km² (10 km separation). (Compare this with Denmark, 1/979 km², 31 km spacing; France 1/3419 km², 58 km spacing). Comparing these resolutions with the suggested separations of Guyot (1998) (rainfall – 15 km; air temperature – 30 km; other synoptic variables – 60 km; sunshine – 70 km; and radiation – 150 km) indicates that the network is adequate for general applications and forecasting, but for agrometeorological support of organic farming however, these resolutions are too coarse; a doubling or tripling of synoptic type weather stations would be required. In some countries a network of automatic weather stations will provide the necessary resolution of data, but an alternative to increasing observation density is to rely on output form numerical weather prediction models. Currently a resolution of 20 km grid spacing is normal and in a few years this will be 5-10 km (25-100 km²). In those parts of the world where observations are poor or low resolution, effort should be made to increase observation density to ensure reliable running of NWP models, thus allowing reliable fine spatial resolution data to be available for organic farm management. A further consideration is that there may be a need to down-scale NWP output to sub-grid size scale in order to account for farm-scale spatial variability in resources and topography. There is a need for further research into the development and reliability of suitable downscaling methodologies. For this approach to work there is also a need to undertake further research into adapting existing, proven agrometeorological models to integrate with NWP output.

Recommendation for organic agriculture:
Focus of research and development is placed on:
implementing, calibrating, testing and using numerical weather prediction to provide fine spatial resolution data for agrometeorological modelling, forecasting and organic farm planning in all world regions where a significant benefit might arise from organic production.
developing integration of NWP output and existing agrometeorological models

1.4.2 Specification of "ideal data"

Meteorological data for organic production needs to be targeted at a number of temporal and spatial scales:

1. Regional weather forecasts – daily and weekly forecasts, updated daily. The regional forecasts should allow farmers to make general decisions about time management on a daily and weekly basis

2. Regional risk forecasts – daily and weekly forecasts, updated daily. The risk forecasts should alert farmers of impending problems of pests, disease, access and severe events thus allowing planned and appropriate response. This is essential because of the lack of choices for post-problem correction.

3. Site-specific risk forecasts – daily and weekly, updated daily. The farmer should have access to either site-specific model output (preferred) or data for running models locally that will provide information about farm scale, local problems that may arise. This should be integrated with the regional forecast services.
4. Site-specific meteorological data – updated in real-time or daily. The farmer should have access to data that will enable models to be run on a local, farm basis for planning and operational management. It may be necessary to use an approach like that of Dozeman et al. (2001) or an alternate methodology to further down-scale NWP output.

First draft specification of meteorological data requirements for modelling processes for organic agriculture:

1. Air temperature – 15 min interval
   - maximum,
   - minimum
   - derive average daily values
   - derive climatic data
   - derive extreme risk probabilities

2. Rainfall – per 0.5 mm rainfall or 15 minute interval
   - continuous
   - derive average daily, monthly values
   - derive climatic data
   - derive extreme risk probabilities

3. Wind – 15 minute interval
   - speed
   - direction
   - derive run of wind
   - derive climatic data
   - derive extreme risk probabilities

4. Solar radiation – 60 minute interval

5. Soil temperature – 60 minute interval
   - maximum,
   - minimum
   - derive average daily values
   - derive climatic data
   - derive extreme risk probabilities

6. Relative humidity – 15 minute interval
   - derive average daily values
   - derive climatic data

7. Evapo(transpi)ration (potential) – 4 hour interval
   - derive average daily values
   - derive climatic data

1.4.3 Agricultural production models

There are a large number of crop production models available for use in agriculture. A search of The Register of Ecological Models (http://dino.wiz.uni-kassel.de/ecobas.html) revealed 122 models related to crop production. It is not appropriate to evaluate all these models in this report, but some specific points can be raised with regard to the demands organic production places on simulation modelling.

The first issue is whether models need to be developed for organic specific production. If a model is empirical, and based on conventional production it is quite possible that analytical error will result from its use for organic management due to working outside the design range of the model. Similar problems can arise if a model is mechanistic. A mechanistic model generally has two layers, an upper predictive layer which functions by interaction with a lower causal layer (Holden, 2001). In many mechanistic models, the lower level will include empirical relationships, or alternatively, the model will be designed to focus on a specific situation (such as the fate of mineral fertiliser N rather than N in general). In either of these cases it is possible that error would result from using the model in an organic context unless it
was encompassed within the model design range. In general, any model that is designed to simulate crop production or the physical environment in a general, wide ranging manner will be suitable for organic agriculture, but care should be taken to establish the credentials and suitability of a model before using it. Normal testing and calibration procedures (Holden, 2001) should be followed when any model is applied in a new situation (physical, geographical or temporal).

<table>
<thead>
<tr>
<th>Requirements for organic agriculture:</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Establish a register of agrometeorological models suitable for use with organic production.</td>
</tr>
<tr>
<td>(2) Identify gaps in the subjects covered by existing models</td>
</tr>
<tr>
<td>(3) Research and develop new models to fill in the gaps for organic agriculture</td>
</tr>
</tbody>
</table>

Farming is all about managing risk, and the organic farmer possibly has less of a risk buffer than the conventional farmer because of the lack of options for curative responses (i.e. the use of agro-chemicals is severely limited) to maintain crop yield potential. For this reason, the development of risk forecasting models is necessary to provide early warning of potential problems. There are a number of approaches to this problem. Models can be developed that simulate the farm’s crop and livestock production. At the outset the models use climatic data, and are continuously updated with real values as they become available. Predicted outputs can be monitored, as can current crop performance. Deviations between actual and predicted can be used as a forecasting tool. Careful site-specific calibration of such models will be required. An alternative type of risk forecasting model is the specific event risk (such as a disease outbreak). In this case, recent, and 5/7 day forecast data are used in a model to predict the onset of problems before they become visible. Analysis of sequences and patterns in the climatic data set may be a valuable aid in this task. Farmers of course, would like to know what is going to happen in the coming season. This is one of the more difficult forecasting issues, but knowledge of whether a season is likely to be good or bad may be valuable in risk management.

<table>
<thead>
<tr>
<th>Requirements for organic agriculture:</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Establish which elements of organic production could be made less risky/more manageable with the development of risk forecasting models</td>
</tr>
<tr>
<td>(2) Develop suitable risk forecasting models</td>
</tr>
</tbody>
</table>

Given that one of the biggest problems that farmers making the transition between conventional and organic production face is the change in time management. Models, or expert systems to assist in new time management regimes are needed. The historical body of knowledge (e.g. 60 year of extensive, mechanised agriculture in Western Europe and North America) associated with conventional production is lacking for organic production. Tools that help in the estimation of job times, field access and machine time requirements may be of great benefit, in association with weather forecasts to help farmers make time and operational decisions effectively. Effective time management requires farmers to analyse job demands in relation to time constraints by asking: What needs to be done? How much time is available? How much time do jobs need? Will a job be quicker/easier under different conditions (e.g. faster speed on a drier soil)? Climate and current season weather data used with crop models should indicate the rate of development in the current year, whether jobs might occur earlier or later (such as weeding, limited interventions) and how long jobs may take. Agrometeorological models should assist with these issues if available and accompanied by suitable data. A good short-term weather forecast should allow an immediate assessment of current needs and priorities and what will be physically possible in the short term (e.g. not spreading if heavy rain). Adjustment of workload according to the nature of the task and the current weather may be possible. Most importantly, weather data will help address the question of whether a task can be completed satisfactorily.
Requirements for organic agriculture:

1. Establish a database of time/operational management tools suitable for organic agriculture
2. Integrate the data requirements of such tools with the forecast services available to farmers

1.4.4 Knowledge gaps

Scialabba (1998) identified a number of issues related to organic production that are of relevance to the assessment of meteorological and climatological issues. These points are evaluated with respect to weather data:

- **Organic agriculture is not practised or studied by many people therefore technical knowledge is limited**
  - The role of weather in organic production has had very little study and few research publications

- **A lack of formal research means that there are many questions remaining about how the system works**
  - Development of organic agriculture R&D should integrate an agrometeorological component

- **A lack of quality information**
  - Suitable resolution data for assisting organic management probably do not exist

- **No knowledge base of specific technical details**
  - Such a knowledge base should include the role of weather and agrometeorological/climatological modelling

- **Few bio-physical studies of organic agriculture in the developing compared to the developed world**
  - The lack of reliable observations in some parts of the world might suggest that NWP has a significant role to play in addressing this issue

- **A lack of hard scientific data**
  - Studies that omit to assess the role of weather when explaining results should be reviewed with care

- **Transferability of knowledge**
  - A crop rotation that might prove excellent in keeping a particular weed within manageable limits in one area might in a different place (with a different climate?) allow infestation of pests. Soil nutrient management varies between agro-ecosystems and even within farms and fields. The role of weather in the development of a knowledge base must be understood

- **Farm practice will depend on the level of technical support available**
  - The agrometeorological community should be developing and supporting the use of models for assisting organic farm management and as training aids for extension workers

- **Networks for dissemination of discovered knowledge are required**
  - The importance of weather in the transferability (or otherwise) of knowledge must be conveyed to farmers
Organic production may be a sustainable approach to food security and environmental protection in a far wider range of environments than currently used.

The integration of weather factors with physical attributes should make land suitability mapping a realistic tool for the development of organic production locally, regionally and nationally.

1.4.5 Available decision making and knowledge management tools

Examples of the types of decision support tools and knowledge management tools that are currently available reveal the type of tools that need to be tested, supported and developed for organic production management. The examples presented here are just that, examples, and not an exhaustive list, rather a flavour of the types of tools that are available. The list can be built upon in the future.

Expert systems are now being developed that can assist with planning of site specific crop rotations such as Multi-Objective Decision Support Tool for Agroecosystem Management (MODAM) (Zander and Kächele, 1999). Bachinger & Zander, 2001 described this tool as being a “rule-based” system that relied on expert knowledge rules derived from experimental sites and farm surveys. The tool does not at present take account of specific climate variation or impacts of changing synoptic situations from year to year, thus it cannot be used for weather risk assessment or outside a limited geographical area. Tziliakis & Lewis (2001) presented a similar decision support tool being developed for managing the transition from conventional to organic production. As with MODAM, this software appears to take no specific account of climate even though it can develop scenarios over a 15 year period. The Agricultural Planning Toolkit (developed through FAO) is a “shell” program that gives users access to a number of software packages for use in agricultural planning. Modules include: Climate Data Analysis, Estimation of Biomass Yield, Crop Modelling System (water requirements for irrigation and yield assessment), Agro-Ecological Zone management, Productivity and Population Potential and Land Evaluation. It appears that this toolkit has not been developed significantly since 1997. A further development of weather integrated planning tools is probably a valuable project for organic production.

Decision Support System for Agrotechnology Transfer (DSSAT) was designed to accelerate the flow of agrotechnology and increase the success rate of technology transfer from agricultural research centres to farmers’ fields as part of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project. IBSNAT developed software which matches crop requirements to land characteristics using crop simulation models, data bases, and strategy evaluation programs (Figure 10). The resulting system provides access to data bases and crop models from a single “front-end” user interface so that the user may "test" on screen the performance of new cultivars, sites, or management practices. This system allows users to screen new products or systems without doing field trials. By simulating outcomes of strategies, "what if" questions can be addressed. As a decision support system, DSSAT helps users make choices that result in desired outcomes, not only now, but next year, and 10, 25, or 50+ years into the future. DSSAT has been used for: (1) global climate studies (Peart et al., 1988; Holden and Brereton, 2001); (2) with geographic information systems (Engel et al., 1997); (3) whole-farm system models (Engel et al., 1997); (4) pest-crop interaction models (Batchelor et al, 1992); (5) fertiliser...
strategy development (Bowen et al., 1998) and (6) plant breeding evaluations (Hunt, 1988; Wortmann, 1998).

DSSAT integrates the following components:

1. A data base management system (DBMS) to enter, store, and retrieve the data needed by the system. Multiple scenarios and management strategies can be built up in the data base. There are four data bases used: Weather (daily weather data); Soil (600 USDA pedons); Inputs (site-specific soil data); Management and experimentation (chronological listing of activities and events for an experiment; summary of pre-plant soil fertility and pre-plant soil water content for each layer; date and fertiliser inputs by plot)

2. A set of tested crop models integrating plant growth and soil components. These models are mainly well established (e.g. the CERES family of models: CERES-maize, CERES-wheat, CERES-rice, CERES-barley, CERES-sorghum, and CERES-millet; the CROPGRO series of models for legumes: CROPGRO-soybean, CROPGRO-peanut, CROPGRO-dry bean (Phaseolus); the CROPSIM model series: CROPSIM-cassava and SUBSTOR-potato, CROPGRO-Tomato, CROPGRO-Chickpea, Sugarcane, Sunflower) but have limitations due to modelling the plant element at a significantly higher level of detail than the soil element (Bouma, 2001)

3. An application program for analysing and displaying outcomes of long-term simulated agronomic experiments. The strategy evaluation program in DSSAT allows users to evaluate the merits of simulated strategies and identify the best one. The program uses cumulative probability functions to develop and select the strategy with the preferred mean and variability characteristics. With this program users can determine the effectiveness of crop management strategies, the economic return of a new cultivar, or the suitability of a site for a specific crop. Using weather generator programs which generate coefficients from historical weather data, DSSAT can simulate the growth and development of a crop for up to 50 consecutive years.

It is hopefully clear from the above description that the integrated modelling environment that is DSSAT should be developed and tested for organic production management and risk planning. Such a tool also has clear potential for management of the transition period to organic production.

The on-line nitrogen/phosphorus/potassium and weather data processing model is an example of an on-line tool that is available to most Internet users. The web site (http://www.qpais.co.uk/mods/cgip.htm) contains a range of models, but four are of specific interest: weather, potassium, phosphorus and nitrogen (Figure 11). As an example of the model operation, the nitrogen model provides an illustration of the level of model development achieved with this on-line system (largely based on the model description at http://www.qpais.co.uk/nable/modinfo.htm):
The model estimates the response of twenty-four C3 arable crops to N-fertiliser and to crop residue incorporation. Variation with time, soil type, cultural practice and weather and be assessed. The model also calculates crop nitrogen and nitrate contents, the distributions of water and nitrate down the soil profile and the amounts of nitrate leached below different depths from the soil surface. Weather files have been prepared to represent the daily mean, temperature, rainfall, and potential evaporation for different parts of the world. To run the model it is first necessary to select the most appropriate weather file and make any adjustments to monthly rainfall based on local data. Although it should be possible to simulate N-response of crops grown in many countries, it must be emphasised that the validity of the model has only been tested in West Europe. In the model the soil is visualised as consisting of 20 consecutive 5 cm thick layers. Roots develop laterally and vertically in the soil. The volume of soil from which they can extract mineral-N increases with plant mass until a stage is reached at which further root development ceases or until the roots reach a hard pan or other barrier to root penetration. Fertiliser and crop debris are incorporated in the uppermost layers of soil. Microbial breakdown of the endogenous soil organic matter always increases soil mineral-N. But mineral-N is either produced or immobilised during the decomposition of crop debris, depending on its C/N ratio. When mineral-N is released it is first converted to ammonium-N which is then nitrified to nitrate-N, which it is assumed, is not absorbed by soil, but it can be taken up by plant roots, can be leached downwards during rain or can move upwards during evaporation from the soil surface.

The example models presented indicate the type of tools that can be made available to farmers considering the change to organic production. The model examples obviously require testing for a wider geographical extent, and it is necessary to confirm the validity of a model's assumptions for an organic system if designed for N-fertiliser management. There is perhaps a role for the organic certification bodies in assessing the suitability of models aimed at farmers for use as management tools.
1.5 INTERACTION WITH THE AGRICULTURAL COMMUNITY

1.5.1 Dissemination of information

Information dissemination is of vital importance. Organic producers have support and interest groups in most of the developed world which are integrated by IFOAM (a list of all members is available at http://www.ifoam.org/links/1.html) and the regional certification bodies. In order for the link between organic production and agrometeorology to be developed and sustained it will be necessary to make users of agrometeorological information demand the services that can be developed by the research community and national meteorological agencies, as well as such groups publicising the tools and services they can offer.

There is far more to the dissemination of agrometeorological information than merely sending it to organic farmers. Training and support for the integration of information technology into daily farm life is also necessary. A review of IT uptake by farmers in Europe (Gelb et al. 1999) ranked limiting factors (by order of importance) as:

- Inability of farmers to use IT
- No perceived benefits - economic and others
- Too hard to use
- Lack of Technological infrastructure
- Cost of technology
- Not useful Information/ not relevant problems
- Fear of technology
- Not enough time to spend on using technology
- Do not understand the value of IT
- Lack of training
- Better alternatives
- Personal impediments
- Lack of integration with other farm systems

- Will not use agrometeorological services and models?
- Can see not reason to use agrometeorological services and models?
- Should model services be provided by advisors?
- Need computers, electricity and reliable telephones
- Poor value for money?
- Possible uses of agrometeorological services and models not sold well enough?
- Agrometeorology perceived as being outside the “core-competency” of the organic farmer?
- Use of model information should become routine for management planning
- Possible uses of agrometeorological services and model not sold well enough?
- Dissemination through user groups essential
- Organic production lacks a long-term knowledge base so this should not be the case
- Technological advances are removing this problem
- ?

It is clear from this list that there is little point in researchers developing tools for organic farmers unless there is a social training and re-education to ensure that the value of agrometeorological tools is understood, and their benefits are made clear.

1.5.2 Potential gains of using agrometeorological data

Scialabba (2000) identified a number of issues related to organic production and its global development, most of which have a significant link to weather and climate:
Soil formation and conditioning

Invertebrates play a central role, combined with plant litter in forming suitable organic matter, creating strong, permanent soil structure thus permitting oxygen, nutrients and water to move in the soil.

Waste disposal

Ecosystems recycle, detoxify and purify themselves using bacteria fungi and invertebrates, provided that their carrying capacity is not exceeded by excessive amounts of waste and by the introduction of persistent (synthetic) contaminants.

Pest control

Complex interactions among predator-prey populations are used for pest control. If a portion of the prey is not available because of environmental discontinuities (a typical case in agriculture), the self-regulating balance will be dampened. Inter-specific competition keeps more pests in check than can be achieved by using pesticides.

Biodiversity

Ecosystem stability depends on the competition between species for food and space. The nature of inter-specific competition and its effects on the species involved is one of the least known and most controversial areas of organic production and its interaction with the wider environment.

Beneficial associations

e.g. symbiosis of roots and mycorrhizal fungi in forests help with absorption of nutrients, transfer of energy and reducing pathogen effects.

Pollination

220 000 out of 240 000 species of flowering plants are pollinated by insects.

Carbon sequestration

The capacity of biomass in sequestrating carbon is receiving increased attention with the aim of reducing climate change.
Where no tillage is practised, soil contributes to retaining carbon.
As organic agriculture favours minimum tillage (for better retention of water, nutrients, and biodiversity), the carbon retention potential of soils is becoming an important issue that requires further research.
Land

Organic farmers attempt to enhance soil fertility. Soil structure is improved through nutrient mining (by deep rooting crops), improvement of nutrient availability with mycorrhizal and optimal nutrient recycling, specific crop rotation and manuring strategies. Minimum tillage avoids soil compaction. Integrating trees and shrubs conserves soil and water and provides a defence against unfavourable weather conditions such as winds, droughts, and floods.

Water

Maintaining water quality requires application of farm practices that avoid pollution and use little water (e.g. minimal use of irrigation, prevention of water evaporation losses). Due to the change in soil structure and organic matter content under organic management, water efficiency is likely to be high on organic farms. Efficient harvesting and use of water also controls salinisation and water logging.

Genetic material

The emphasis of seeds and breeds used in organic agriculture is on local suitability with respect to disease resistance and adaptability to local climate. The availability of suitable genetic material (e.g. GMO-free), its selection, rearing and distribution is often a constraint.

Fertilisers and pesticides

Decreasing the use of synthetic fertilisers and pesticides goes together with increasing other inputs (such as manure), or specific management strategies such as timing of planting or rotational combinations. Crop protection relies on natural pest controls (e.g. insect pheromones, plants with pest control properties) or by enhancing self-regulation.

Crop rotation

Crop rotation is required under organic certification programmes and is considered to be the cornerstone of organic management. Crop rotation is a valuable tool for weed control, maintenance of soil structure and organic matter, recycling of plant nutrients, contribution to overall species and habitat diversity, preventing erosion, green manuring, and pest and disease control. The success of an organic farm depends on the identification of end-uses and/or markets for all the crops in the rotation, as few farmers can afford to leave fields fallow.
Energy

Energy is required at all points of the food production chain: land preparation, planting, harvesting, transport, processing, irrigation, agro-industries and rural services (e.g. cooking, heating, and lighting). On organic farms, mechanization is often replaced by labour, especially for weeding and harvesting in highly diversified systems. Discarding synthetic fertilizer may result in escalating thermal and mechanical energy inputs for weeding and tillage. In appropriate management of energy inputs used in organic agriculture may be detrimental to the environment but because environmental standards usually only reflect local pollution minimization this effect may not be visible. An holistic view of energy consumption is required.

Diversification

Organic agriculture requires a diversity of crops and livestock

Stability and resilience

A system’s resilience is its ability to overcome perturbation and to recover its function to former levels once the perturbation is removed. Resilience is of particular value to farmers in terms of risk and productivity of the system. In organic agriculture in general, a diversity of crops is grown and different kinds of livestock are kept which spreads the production risk. There is less chance of a bumper year but less chance of low production for all crops and livestock simultaneously. This contributes to food security and stability of food supply

Yields

Factors determining yields include plant varieties, manipulation of the biological processes, the physical environment, management systems, time and length of the growth period and climate. Improved yields are possible by conversion to organic production from traditional production except where extensive high-input agriculture is the norm

Total farm production

The total production of a farm is the yield multiplied by the area in the different crops or that used for livestock (usually measured per unit of area). When measuring production, one needs to consider net production, not just outputs
Further specific issues that have become apparent during the preparation of this report include:

**Conversion planning**

Suitability mapping, problem prediction, workload management
- Climate
- Synoptic situation
- Forecasting

**Crop selection**

The selection of the right crop for the climate, and its integration into a crop rotation are crucial
- Climate
- Season lengths
- Incident radiation
- Day lengths
- Cloud
- Wind
- Temperatures
- Precipitation

**Housing design**

Animal welfare is a fundamental principle of organic production. The design of animal housing has got to be the best possible. Housing design should include a consideration of the waste storage and dirty water storage requirement to ensure pollution management is also possible
- Climate
- Temperature
- Season lengths
- Soil water balance

**Timing optimisation**

For organic agriculture to function at its best it is necessary to optimise the timing of all management activities. The weather is the most important factor in timing management to minimise: soil damage, pollution risk, pest and disease infestations, erosion and runoff losses amongst others
- Synoptic situation
- Precipitation
- Wind
- Temperature
- Humidity
- Soil water balance
- Forecasts

**Warnings, Alerts and Alarms**

Advanced knowledge of severe to catastrophic events will allow for some preparation and minimisation of the impact on the farm enterprise
- Forecasts
- Synoptic situation

1.6 SUMMARY OF FINDINGS

term of reference a)

To define properly the mentioned fields of agricultural production:

“Organic agriculture is a holistic production management system which promotes and enhances agro-ecosystem health, including bio-diversity, biological cycles, and soil biological activity. It emphasises the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, cultural, biological and mechanical methods, as opposed to using synthetic materials, to fulfil any specific
function within the system. An organic production system is designed to: (a) enhance biological diversity within the whole system; (b) increase soil biological activity; (c) maintain long-term soil fertility; (d) recycle wastes of plant and animal origin in order to return nutrients to the land, thus minimising the use of non-renewable resources; (e) rely on renewable resources in locally organised agricultural systems; (f) promote the healthy use of soil, water and air as well as minimise all forms of pollution thereto that may result from agricultural practices; (g) handle agricultural products with emphasis on careful processing methods in order to maintain the organic integrity and vital qualities of the product at all stages; and (h) become established on any existing farm through a period of conversion, the appropriate length of which is determined by site-specific factors such as the history of the land, and type of crops and livestock to be produced."

term of reference b)

To determine the most important agrometeorological and agroclimatological aspects of the mentioned fields of agricultural production:

<table>
<thead>
<tr>
<th>Animals</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outdoor days</strong></td>
<td>Organic systems require a reasonable duration of outdoor days in order for the animals to have a life similar to that which may be expected naturally. A greater number of outdoor days also makes management of feed easier to achieve in an organic manner.</td>
</tr>
<tr>
<td><strong>Calving conditions</strong></td>
<td>Calving should occur outdoors therefore the risk of extreme weather (particularly wet and cold) should not be excessive.</td>
</tr>
<tr>
<td><strong>Grass production</strong></td>
<td>The available land area will dictate the number of animals that can be supported in conjunction with the grass growth rates (which will be weather limited). The grass production will dictate both the direct feed and the silage production. The climate and soil will dictate the number of animals that can be supported with reasonable risk.</td>
</tr>
<tr>
<td><strong>Clean pasture</strong></td>
<td>Clean pasture systems are a first line control of pests, particularly parasites. The grass growth and land area will dictate how much clean pasture is available over the course of the year and the climate will probably dictate the duration of parasite survival.</td>
</tr>
<tr>
<td><strong>Soil damage</strong></td>
<td>The soil type, in conjunction with the weather/climate will dictate the type and magnitude of potential soil damage. This factor is related to both grass growth and outdoor days.</td>
</tr>
<tr>
<td><strong>Weed control</strong></td>
<td>Sheep are a leading method of weed control and thus accessibility, health and soil damage must be considered and all are limited by climate.</td>
</tr>
<tr>
<td><strong>Free range hens</strong></td>
<td>Sufficient land area, access and feed supply are required. In the case of feed supply the quality of feed available on the range has to be matched by varying quality of grain fed to ensure no wastage. The stock density will be limited by the land available to grow supplemental feed or its regional availability both of which will be climate limited.</td>
</tr>
</tbody>
</table>
### Crops

<table>
<thead>
<tr>
<th><strong>Crop climate limits</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual crops have to be assessed to ensure they will function as a suitable economic product given climate limitations and to ensure balanced crop rotations are possible for nutrient management</td>
</tr>
</tbody>
</table>

| **Sowing date** |
|-----------------
| The best crops have to be chosen, but a total cover should be maintained because gaps allow weeds to develop, thus the start of the cycle for each crop has to be linked |

<table>
<thead>
<tr>
<th><strong>- Temperature</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The progression through growth stages will be largely influenced by temperature and the seasonal characteristics</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>- Degree days</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>By matching variety to growth potential the crop health and cover can be carefully maintained at an optimum level</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>- Photoperiod</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>There must be sufficient light available for the crop to be the dominant species in the field and for it to develop optimally</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Water requirement</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate will dictate whether there is enough water available naturally, and the regional demand where irrigation will be necessary. In addition side effects of irrigation will be partially influenced by climate.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Timing of harvest</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The combination of the above factors will dictate harvest data. The crops chosen should offer little risk based on the regional climate. The risk of poor harvest due to the onset of bad weather should also be considered.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Fodder crops</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Can be grown but never back-to-back because of infestation risks</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Cereals</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Have to offer a high return so conditions must be <em>ideal</em>, not adequate as might be possible with conventional production</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Swards</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed species and legumes offer the best soil/pest/weed management options</td>
</tr>
</tbody>
</table>

### Tillage

<table>
<thead>
<tr>
<th><strong>Access</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate, along with soil will dictate when access to a field is possible: trafficable days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Method</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Likelihood of soil damage and the need for weed control will influence the choice of method. Soil workability will be crucial</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Number of passes</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil damage and weed control and frequency/duration of access will be weather controlled</td>
</tr>
</tbody>
</table>

---

**To determine the most important management aspects in the mentioned fields of agricultural production that have agrometeorological and/or agroclimatological components:**

- Soil formation, conditioning and nutrient levels
- Erosion and pollution
- Waste disposal
- Pest control
- Weed control
- Pollination
- Carbon sequestration
- Land
To review conditions and measures to optimise agricultural production in the mentioned fields where agrometeorology can play an important role:

- Risk modelling
- Crop production modelling
- Time management support
- Land suitability classification
- The conventional to organic transition period
- Provision of fine spatial (<100 km²) and temporal (15-60 minute interval) meteorological data, possibly from Numerical Weather Prediction models
- Provision of a body of tested simulation models suitable for organic production management, preferably integrated in a geographical information system

References


Smith, L. P. 1956. Potato blight forecasting by 90 per cent humidity criteria. Plant Pathology 5: 83-87


CHAPTER 2

SUMMARY OF FINDINGS ON URBAN AGRICULTURE

term of reference a)

To define properly the mentioned fields of agricultural production:

- Urban agriculture is "farming and related activities that take place within the purview of urban authorities ... [where urban authorities are] the panoply of laws and regulations regarding land use and tenurial rights, use of water, the environment, etc, [sic] that have been established and are operated by urban or municipal authorities. Urban agriculture takes place within certain boundaries which may extend quite far from an urban centre, while peri-urban agriculture takes place beyond that often geographically precise boundary, although its own outer boundary may be less well defined." (Aldington, 1997)

- "Urban agriculture is defined as the procurement of food products through crops, animal husbandry, forestry and aquaculture within urban zones and in fringe areas, for improving the nutrition of population groups, generating employment and income for individuals or groups of individuals, assisting environmental sanitation through recycling waste waters and solid wastes." (Red Agricultura Urbana Investigaciones Latinoamerica www.idrc.ca/cfp/aguila_e.html#News)

- "Urban agriculture has been defined as ... an industry that produces, processes and markets food and fuel, largely in response to the daily demand of consumers within a town, city or metropolis, on land and water dispersed throughout the urban and peri-urban area, applying intensive production methods, using and reusing natural resources and urban wastes, to yield a diversity of crops and livestock." (Cropper, 1996)

- "Urban agriculture refers to producing food and fuel within city or town areas directly for the urban market (including street vending and home consumption). The products are usually processed and marketed by the producers and their close associates. It includes: crop and animal production on roadsides, along railroads, in backyards, on rooftops, within utility rights of way, in vacant lots of industrial estates, on the grounds of schools, prisons and other institutions, etc.; aquaculture in tanks, ponds and rivers; orchards and vineyards; trees in streets and backyards, on steep slopes and along rivers; and the recycling and use of urban organic wastes (waste water and solid waste) as resources, i.e. converting open-loop "disposal" systems in closed-loop "re-use" systems." (de Zeeuw et al., 1998)

- "Urban Agriculture: any and all enterprises, commercial and non-commercial, related to the production, distribution, sale or other consumption of agricultural and horticultural produce or commodities in a metropolitan / major urban centre." (www.cityfarmer.org/Asiancities.html#asian)

- "Urban agriculture or food growing encompasses the production of all manner of foodstuffs, including fruit and vegetable growing, livestock rearing and beekeeping, at all levels from commercial horticulture to community projects to small scale hobby gardening." (Garnett, 1996)

term of reference b)

To determine the most important agrometeorological and agroclimatological aspects of the mentioned fields of agricultural production:

The normal weather influences on plant growth apply to urban agriculture. The combination of urban location and indoor techniques can results in crop production
in areas that would not normally be suitable, but there are a number of urban specific influences that need to be considered:

- Climate: the regional climate will be greatly influenced by the urban fabric. In addition, cities have a large number of micro-climates. The possible magnitude of climate change (predicted as a global temperature rises of between 1 and 3.5°C by the year 2100) has already occurred in some big cities. At night cities are usually warmer than their rural surroundings because of heat stored in bricks and concrete and trapped between close-packed buildings - the so-called urban heat island effect. Temperatures are usually greater in the centre of the city, with a dome-like profile. City wind speeds are lighter, on average, and vary from place to place. Wind "tunnels" and "hot-spots" occur where winds are channelled down city streets or wash down the faces of tall buildings. By contrast, streets running perpendicular to the wind direction are sheltered, to the extent that pollutants may not disperse. Paved surfaces mean that runoff from rainfall reaches a higher peak flow in urban areas, and reaches it much faster. As the city grows, the climate changes intensify.

- Meteorology:
  - Rainfall: The urban farmer is competing for water with other domestic users. While intensive irrigation may be possible for short periods, rainfall capture is necessary for sustained crop growth. Seasonality of rainfall may be an issue. The city of Vancouver subsidises rain barrels for water conservation. Hose-pipe bans are common in UK and Ireland when water supplies to urban areas become restricted in summer months. In less developed areas, urban agriculture will compete with day-to-day life for available water. Flooding and storm damage can also be problematic.
  - Radiation: Radiation is essential. Direct sunlight can be a problem. If buildings shade a site (particularly in the morning) then the available radiation will be reduced and yield will be poor. If a site is in direct sunlight all day (particularly when temperatures are high (e.g. tropics), then shade will be necessary. Sites used for growing cash crop for household income supplement should, where possible be inclined to achieve the best possible radiation capture
  - Temperature: urban heat island may elevate ambient temperatures and boost plant growth slightly. The presence of reflective walls and shading features may make the temperature pattern over the growing plot very variable in space and time. This may make the production of a reliable, uniform crop quite difficult
  - Humidity: high humidity levels are common in cities, particularly in the tropics and maritime locations. This has an influence of pest and disease occurrence and the quality of the product. Urban livestock health is closely related to relative humidity
  - Wind: exposure at height on large buildings requires wind protection (but this must not interfere with incoming radiation management). The urban canyon effect (increased wind due to buildings and other structures) can cause artificially high wind speeds, as can fast moving traffic on urban freeways
  - Air quality: research has shown that ambient air pollution in and around cities can have serious effects on the yield of important agricultural crops. This has been demonstrated by field or chamber studies in India, Pakistan and Egypt. Air quality can impact on nutritional quality and yield. Plant populations in cities should improve air quality

term of reference c)

To determine the most important management aspects in the mentioned fields of agricultural production that have agrometeorological and/or agroclimatological components:

- Siting of crops/fields (available radiation, shade, water supply)
- Water availability: recycling water, salination regulation
- Yield and quality control
• Protective measures

term of reference d)

**To review conditions and measures to optimise agricultural production in the mentioned fields where agrometeorology can play an important role:**

• Urban weather forecasts
• Extreme event forecasts
• Tailored forecasts for neighbourhoods?

**References**


**Internet:**

www.cityfarmer.org
3.1 WHAT IS INDOOR AGRICULTURE?

Indoor agriculture is a production system that uses protection structures for growing plants, usually with plastic or glass coverings, to avoid or lessen the effects of abnormal weather. The system helps to conserve heat and to maintain a favourable temperature and humidity environment for growing and developing plants which results in better harvests.

Indoor agriculture is not simply about protecting crops. It uses similar methods to those employed in conventional outdoor agriculture but creates artificial conditions for improved productivity.

3.1.1 Scope

Indoor agriculture (also including the technical process known as "plasticulture") has been applied in many countries around the world since 1960. Good results obtained by this approach mean that the system has seen increased use during the last few years. The use of covering structures has increased productivity and hence the competitiveness of farmers both nationally and on the international markets that are part of the globalised commercial world of the 21st Century. This report will focus on crop production under structures rather than animal production. It will not include a discussion of non-structured plasticulture (as is used for production of maize in marginal areas like Ireland) where plastic is used in conventional field production to create a specific microclimate for the crop during early development.

There are two kinds of indoor agriculture: plastic agricultural tunnels and greenhouses. Greenhouses are made with structures that helps control climatic conditions under which crops develop. The covering allows the transmission of radiation from the sun into the structure, which then traps heat and radiation from the soil. This is known as the "greenhouse effect" (Figure 1). The term "plasticulture", refers to the use of polythene tunnels, rather than greenhouses. This has tended to be less widely used but, nevertheless is an important application of indoor agriculture. In this report the differences between glass and plastic structures will not be emphasised unless it is of direct significance to the point of discussion.

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Figure 1: The greenhouse effect
Generally a greenhouse protects plants against adverse climatic conditions (such as hailstorms, excess of rainfall, heavy winds and frost), and permits farmers to obtain greater and better yields. Indoor agriculture is important because it permits the cultivation of areas where some years ago it seemed impossible to produce viable crops.

Greenhouses represent the most common application of indoor agriculture (Figure 2). In greenhouses, three of the four factors of outdoor agriculture are controlled, but the fourth cannot be controlled. Temperature, soil, and moisture are adjusted as necessity demands, but incident radiation is controlled by to geographical and microclimate conditions.

Nevertheless the roof material should be chosen according to local conditions to get the maximum benefit from its use.

3.1.2 History

Greenhouse coverings are a matter of historical record since the Roman Emperor Tiberius. He had a mica-covered "specularium" built in 30 AD. Since the 1960s, until today, in most parts of the world countless greenhouses can be seen. The efficiency of indoor agriculture is demonstrated by comparing the yields obtained with conventional agriculture versus production in greenhouses. The coverings are not only used to control water supply, but to protect crops against adverse climatic conditions in all of the phases of their development.

There are many conditions that can combine to achieve good production in greenhouses. The two most important are microclimate and the regulation of photosynthesis. Greenhouses allow control of many microclimatic factors (particularly optimum temperature and humidity) leading to better harvests with high quality produce. These produce achieve better prices at market, and it is also possible to control the time of harvest. If timed when conventional production is off-season market prices will be higher for indoor grown crops. The regulation of photosynthesis is possible inside a greenhouse because diffuse light can be provided to plants (without shadows and high contrast) in conjunction with the control of temperature and humidity. This provides better conditions for plant growth.

3.1.3 Rationale and goals

There are many benefits from indoor agriculture. The most important are: a) protection against damage by UV light; b) improved ambient temperature conditions; c) protection of crops from adverse climatic conditions; c) increased productivity; d) reduced production costs; e) controllable harvest timing; and f) better product quality. Some specific considerations are:

More Yields

It is possible to get more production per area. Depending on the crop, its handling and the optimum combination of many variables, the yields can increase between four and
twelve times that normally obtained without protection. This can lead to better food security and can give better products for domestic and international markets.

Lower Production Costs

Any system that reduces the use of fertilisers, water and other agricultural inputs, and at the same time lowers the risks of undue weather influence (e.g. hail, frost, strong wind, excessive rainfall, drought, high or low temperatures,...) will cause gross margins to increase, while the risk of failure will decrease.

Better prices

- The opportunity to obtain premium prices comes from:
- Good management and microclimate control
- A programmed harvesting calendar to obtain better yields during conventional low production times
- Premium prices, due to better management, low use of pesticides and high quality product
- Better quality, weight, shape and size are factors also very important for market value

Quality

Good management is the way to obtain high quality, because the product will be clean, healthy, well graded and have a greater post-harvest durability.

Lower use of water

Generally, technically advanced irrigation is applied inside greenhouses (micro spray, dripping irrigation, ferti-irrigation using programmes for fertilisation together with programmes for irrigation), therefore water wastage is minimised.

Early Harvest

Indoor agriculture permits a shorter time for production and an earlier harvest. The earlier harvest results in more production per year and per unit surface area of land holding.

Pest and disease control

Producing under controlled conditions permits better management of pests and diseases. Low use of pesticides cuts production costs, and creates a safer working environment as well as more desirable product.

Indoor agriculture has some disadvantages. These include: (i) the high initial investment cost related to the infrastructure required; (ii) damage to infrastructure can occur (without good management) and is very expensive to rectify (e.g. wind damage to a poly-tunnel); and (iii) there is a risk of thermal inversion inside the structure causing very-undesirable, and potentially catastrophic conditions for the crop.

3.1.4 Major crops produce

The major crops produced are flowers (e.g. rose, tulip, carnation, chrysanthemum, gladiolus,...) horticultural vegetables and fruits (e.g. pepper, tomato, melon, watermelon, grapes, cucumber, strawberry,...) and specialist crops typical of specific geographical locations and climatic conditions.
3.1.5 Geographical occurrence

Around the world it is common to see greenhouses everywhere. It is estimated that over 500 000 ha, principally in Asia (67%) and Europe (26%) are under indoor agriculture. The distribution by geographical areas in two principal zones: the Mediterranean is about 30% of world glasshouse production and south Asia is approximately 60%. China is the biggest country with greenhouses (200 000 ha), the second is Japan (60 000 ha), the third is Spain (43 000ha).

3.2 AGRONOMY OF INDOOR AGRICULTURE

Indoor agriculture coverings and structures for various applications, depending of crops, the zone or the factor that is to be controlled (e.g. temperature, evaporation, improved use of fertilisers, protection against some ultra violet radiation (UV) or adverse climatic conditions).

3.2.1 Crop selection

The majority of crops can be grown under plastic coverings, the exception could be tree crops due their height once fully developed. Nursery tree stock however can benefit form protection structures.

3.2.2 Land preparation

Soil preparation is different from that needed for outdoor agriculture. Normally production is managed in beds, the machinery needed is limited (only used for medium to large cultivation areas) and in some cases, the soil is brought in from other places. In greenhouse production soil is not always the support medium for the crops. On occasions inert substrates such as perlita, vermiculita, sand, sawdust, rice cracker, volcanic stone, bone flour or blood are used. Alternatively, "hydrophonic" technology is used. This is simply providing water with a nutrient solution and mechanically supporting the plant. No soil substrate is required.

3.2.3 Sowing

Similar sowing activities are used in indoor agriculture to conventional. Soil preparation normally uses two cultivation passes and a rolling stage. It is very important to use organic material incorporation (e.g. cattle slurry) to maintain soil structure and water holding capacity.

3.2.4 Management

3.2.4.1 Construction

Greenhouses can be made with many materials: wood, bamboo cane (*Guadua angustifolia*), galvanised steel, galvanised aluminium, mixed metal and wood or metal pipe frames. The principal function is to create a structure for microclimate control at a suitable investment cost. The structure also has to be durable enough to withstand strong winds and hailstorms.

3.2.4.2 Location

Greenhouses should be located where they get maximum sunlight. Is preferable that all day sunlight is available, but a minimum requirement is morning radiation to allow plants
metabolism (food production) early in the day to get maximum growth. In some plants it is necessary to provide shade during the day (usually in the afternoon) because they naturally need less light for growth. Other considerations include the proximity to sources of heat, water, electricity and protection against strong wind. Near a greenhouse, there should be a place for storage of tools and supplies, and access to it should be convenient for both people and utilities.

3.2.4.3 Types of greenhouses

When deciding on the type of structure, it is necessary to plan adequate bench space, storage space, and room for future expansion. Large greenhouses are easier to manage because temperature in small ones fluctuates more rapidly. Small greenhouses have a relatively large exposed area through which heat is lost or gained, and the air volume inside is relatively small, therefore, the air temperature changes quickly in a small greenhouse. The range of frames can vary from simple to complex structures, depending of the necessities, the imagination of the designer and any engineering requirements. The major types available (Figure 3) are:

Quonset

A simple and efficient construction with an electrical conduit and galvanised steel pipe frame. The frame is semi-circular and usually covered with plastic sheeting. Quonset side wall height is low, which restricts storage and headroom.

Gothic

The frame construction is similar to Quonset, but it has a taller arch shape. Wooden arches may be used and joined at the ridge. The gothic shape allows more headroom than the Quonset frame.

Rigid frame

These structures have vertical side walls and rafters for a clear-span construction. There are no columns to support the roof. Glued or nailed plywood squares make the side wall and allow maximum headroom and air circulation. A good base is necessary to support the lateral load on the side walls.

Post and rafter

A simple construction of embedded posts and rafters. This requires more wood or steel pipe than some other designs. Strong side wall posts must be deeply embedded to withstand outward rafter forces and wind pressures. Like the rigid frame, the post and rafter design allows more space along the side walls and efficient air circulation.

"A" frame

The "A" frame design is similar to post and rafter construction except than a collar beam ties the upper parts of the rafter and there are no separate side walls leading to a reduction in headroom.
3.2.4.4 Coverings

It is very important to make the best election of covering material in order to protect the investment. The choice depends on the kind of plants to be grown inside. To choose the covering it is necessary to consider the geographical location, the maximum, minimum and average temperatures, the possibility of frost, the wind climate, relative humidity, rainfall distribution, rainfall intensity, solar radiation and the crops that are going to be grown. There are various types of covering that can be summarised as: a) glass: the traditional covering that has a good appearance, is inexpensive to maintain and has a very long life; b) fibreglass: lightweight, strong, and practically hail proof; c) double wall plastic: rigid double-layer plastic sheets of acrylic or polycarbonate are available to give long-life, heat-saving; d) film-plastic: structural costs are very low because the frame can be lighter and plastic film is inexpensive; e) coverings that block UV: used in cold climates, but is not efficient for a long periods of extreme cold or frost; f) thermal coverings: used in zones with extreme cold temperatures with long periods of winter conditions or with frequent frost. Each covering will be considered in a little more detail:

Glass

Glass is the traditional covering that has a good appearance, is inexpensive to maintain and has a very long life. An aluminium frame with glass covering provides a maintenance-free, weather tight structure that minimises heating costs and retains humidity. The use of glass is compatible with straight-edged structures. Commonly tempered glass is used because it is two to three times stronger than regular glass, which may be important where hailstorms are likely to occur.

The disadvantage of glass is that it can break easily, is initially expensive to build with, and requires strong frame construction. A good foundation is necessary, and the frames must be rigid, strong and must fit together well to support the heavy glass rigidly.
**Fibreglass**

Fibreglass is lightweight, strong, and practically hail proof. A good grade of fibreglass should be used because poor grades discoulour and reduce light penetration. Only clear, transparent, or translucent grades can be used for greenhouse construction. Polyvinyl fluoride-coated (e.g. Du Pont Tedlar) fibreglass lasts 15 to 20 years. The resin covering the glass fibers will eventually wear off, allowing dirt to be retained by exposed fibers. A new coat of resin is needed after 10 to 15 years. Light penetration is initially as good as glass but can drop-off considerably over time with poor grades of fibreglass or poor maintenance.

**Double-wall plastic**

Rigid double-layer plastic sheets of acrylic or polycarbonate are available to give long-life, heat-saving covers. These covers have two layers of rigid plastic separated by webs. The double-layer material retains more heat, so energy savings of 30 percent are common. The acrylic is a long-life, non-yellowing material; the polycarbonate normally yellows faster, but usually is protected by a UV-inhibitor coating on the exposed surface. Both materials carry warranties for 10 years on their light transmission qualities. Both can be used on curved surfaces; the polycarbonate material can be curved the most. As a general rule, each layer reduces light by about 10 percent. About 80 percent of the light filters through double-layer plastic, compared with 90 percent for glass.

**Film plastic**

Film-plastic coverings are available in several quality grades and several different materials. Generally, these are replaced more frequently than other covers. Structural costs are very low because the frame can be lighter and film-plastic is inexpensive. Severe weather can therefore be a problem. Light transmission by film-plastic coverings is comparable to glass. The films are made of polyethylene (PE), polyvinyl chloride (PVC), copolymers, and other materials. A utility grade of PE will last about a year and should be available at local hardware stores. Commercial greenhouse grade PE has ultraviolet inhibitors in it to protect against ultraviolet rays; it lasts 12 to 18 months. Copolymers last 2 to 3 years. New additives have allowed the manufacture of film plastics that block and reflect radiated heat back into the greenhouse (as does glass), which helps reduce heating costs. PVC or vinyl film costs two to five times as much as PE but lasts as long as five years. However, it is available only in sheets four to six feet wide. Plastic films tends to electro-statically attract dust from the air, so must be washed occasionally to maintain light transmission. There are many kinds of polythene for greenhouses, and it is necessary to find the correct film for a specific crop.

**Coverings that block UV**

These types of coverings are used in cold climates, but are not efficient for long periods of extreme cold or frost. They are stabilised with nickel (which gives a yellowish-green tone). In some regions, particularly in warm climates, high roof greenhouses with big zenithals windows are constructed with anti-insects mesh that also acts as a UV protector, but without any complete seal against the elements.
Thermal Coverings

These are used in zones with extreme cold temperatures, long periods of winter conditions or frequent frosts. During the day heat accumulates inside the greenhouse. Care has to be taken to avoid excess heating above the threshold maximum temperatures tolerated by the crop. The heat is retained during the night thus avoiding temperature drops below that which would effect plant growth (resulting in deviation from normal development and yield).

The films with thermal qualities must also block the UV radiation under 315 nm, but remain permeable to other solar radiation. The thermal energy from the Infra Red (IR) radiation that comes from the soil and the plants should be retained. It should also minimise problems of water condensation, have a long life and the investment must be favourable in relation to the cost-benefit. The colour of these films are variable from white pearl (milky) to light yellowish-green. The latter are recommended for cloudy and rainy climates.

Light diffusion

The ideal plastic film has good light diffusion from the source, reduced shadowing and diffusion thus letting plants receive light on all surface and not only in incidence areas. This property is very important, because it lets the plant use all energy uniformly in order to achieve better photosynthesis and yield throughout the structure.

3.2.5 Harvest

Harvesting processes in indoor agriculture are similar to conventional production. It is difficult to apply mechanical harvesting except over very large surface areas. Some advantages of indoor agriculture are:

- better environmental conditions
- management by phases
- easy to work
- day and night labour
- choose market conditions
- high quality of products

3.2.6 Post-harvest considerations

Indoor agriculture has similar post-harvest considerations as for conventional field agriculture. Some activities must be taken in mind:

- products treatment (hot water, pesticides,...)
- storage temperature and humidity
- transportation temperature and humidity
- time from harvest to final market
- choose better markets and higher prices

3.3 AGRO-ENVIRONMENTAL INFLUENCES ON PRODUCTION BY INDOOR AGRICULTURE

3.3.1 Climatic requirements and limitations

Most world climates are appropriate for indoor agriculture. It is possible to manage microclimatic conditions inside greenhouses using many technical tools like fans, heaters, mist machines, foggers, and ventilators. This makes it possible to cultivate exotic crops all around
the world. Only in locations with extreme conditions (deserts, near the poles, high altitudes, areas with strong winds,...) do difficulties arise because of the complexity of managing external climatic influences. The highest production cost for indoor agriculture is probably the energy consumption for climate regulation (mainly temperature and humidity).

3.3.1.1 **Environmental Control Systems**

Greenhouses provide a shelter against adverse climatic conditions, at the same time they provide an environment adequate for maintaining plants in good conditions. Solar radiation provides sunlight and heat, but it is also necessary to install systems that regulate the environment inside of greenhouse. These systems comprise of: heaters, fans, thermostats, and cooling equipment.

**Heating**

Depending on location, the temperature required by the plants, the kind of greenhouse construction and the total sun exposure, the required heat input will vary from area to area. Sunlight in some locations does not provides enough heat inside greenhouses therefore it is necessary to use additional heating which helps to obtain the necessary day- or night-time temperature. Heating systems can be fueled by electricity, gas, oil, or wood. The heat can be distributed by forced hot air, radiant heat, hot water, or steam. The choice of a heating system and fuel depends on locally availability, the production requirements of the plants, cost, and individual choice. For safety reasons, and to prevent harmful gases from contaminating or damaging plants, all gas, oil, and wood burning systems must be properly vented to the outside. Fresh-air vents must supply oxygen for burners for complete combustion. Safety controls, such as safety pilots and gas shutoff switches, should be used as required. Portable kerosene heaters (as used in homes) are risky because some plants are sensitive to the gases formed when the fuel is burned. Normally 220 volt electric heaters work well and are clean and efficient. Small gas or oil heaters designed to be installed through brick walls are perhaps better because of more efficient heat distribution. Separate solar energy collection and storage systems are large and require much space, but they reduce fossil fuel consumption. One cheap method of storing solar energy is to paint containers black to attract heat and to fill them with water to retain the heat. However, because greenhouse air temperature must be kept at plant-growing temperatures, the greenhouse itself is not a good solar heat collector.

To calculate the heating requirement of a greenhouse (in its simplest form) the following calculation is possible (the example is based on US dimensions, not the more correct SI units and is presented to illustrate the importance of climate to indoor agriculture). Firstly calculate the surface area of the greenhouse where: H = height to eaves; L = length; W = width; R = height to ridge; and S = length of roof slope (Figure 4). Assuming a single layer glass greenhouse with glazing to ground level (double-glazed structures (glass or polycarbonate) reduce the heat requirement by about 30%), the total inside surface area of the greenhouse is: surface area of walls and roof slope = 2 x (H + S) x L; surface area of end walls = (R + H) x W; therefore the total inside surface area (SA) = [2 x (H + S) x L] + [(R+H) x W]. (For the example in Figure 4 this should be 396 square feet). Next the temperature difference between the inside and outside of the greenhouse has to be calculated which is dependent on the crop being grown and the “average lowest winter” temperature. Multiplying the total inside surface area (in square feet) by the temperature difference (in Fahrenheit) indicates the British Thermal Units required to heat the greenhouse. This value can be divided by 3.413 to derive the kilowatt hours which can be used to estimate the heating cost.
Air circulation

Installing circulating fans (Figure 5) in a greenhouse is a good investment. The purpose of circulating fans is to maintain uniform temperatures throughout the greenhouse. Without air mixing fans, the warm air rises to the top and cool air settles around the plants on the floor, thus reducing the benefit of heating the greenhouse. The fan in a forced-air heating system can sometimes be used to provide continuous air circulation, but must be wired to an on/off switch so it can run continuously, separate from the thermostatically controlled burner. The integration of fans in the structure can reduce the heating cost by ensuring that heated air is near the plants at all times.

Ventilation

Ventilation is used to exchange air between the inside and outside of the structure as a means of temperature, moisture, and carbon dioxide (CO₂) control. Several ventilation systems can be used. Natural ventilation uses roof vents on the ridge line with side inlet vents (louvers). Warm air rises on convective currents to escape through the top, drawing cool air in through the sides. Mechanical ventilation uses an exhaust fan to move air out one end of the greenhouse while outside air enters the other end through motorized inlet louvers. Exhaust fans should be sized to exchange the total volume of air in the greenhouse at a range of rates adjustable to the particular crop being grown. Ventilation requirements vary with the climate, the current weather, the season, and the greenhouse usage. Integrated automatic control systems should be compatible with the local climate.
Cooling

Air movement by ventilation alone may not be adequate in the middle of the summer. The air temperature may need to be lowered with evaporative cooling. Also, the light intensity may be too great for the plants. During the summer, evaporative cooling, shade cloth, or paint may be necessary. Shade materials include roll-up screens of wood, aluminium and vinyl netting, and paint.

Small package evaporative coolers (Figure 6) have a fan and evaporative pad in one box to evaporate water, which cools air and increases humidity. Heat is removed from the air to change water from liquid to a vapour. Moist, cooler air enters the greenhouse while heated air passes out through roof vents or exhaust louvers. The evaporative cooler works best when the humidity of the outside air is low. An alternative system, used in commercial greenhouses, places the pads on the air inlets at one end of the greenhouse and uses the exhaust fans at the other end of the greenhouse to pull the air through the house.

Another system of cooling is a "mist irrigation" spray, that consist of very fine drops of water directed at the floor. This reduces the temperature while at the same time increases the relative humidity inside greenhouse.

CO₂ and Light

Carbon dioxide and light are essential for plant growth. As the sun rises in the morning it provides light energy and plants begin to produce food energy (photosynthesis) internally. The CO₂ concentration in the greenhouse falls as it is used by the plants. Ventilation systems are required to replenish the CO₂ in the greenhouse. CO₂ and light complement each other, therefore electric lighting, combined with CO₂ injection, are used to increase yields of vegetable and flowering crops. Bottled CO₂, dry ice, and combustion of sulphur-free fuels can be used as CO₂ sources.

3.3.1.2 Specific climate elements

Climate elements must be managed to achieve good performance from indoor agriculture. The environmental control systems have been considered, and in the next section, the role of specific elements will be briefly described.

Radiation

The covering of an indoor agriculture structure is important with respect to its durability and also its optical properties. Specific aspects include:

- visible light transmission is important because its is essential for plant photosynthesis
- transmission of long-wave infrared (1450 - 730/ cm) out of the structure must be as low as possible in order to maintain the temperature inside greenhouse. If the greenhouse does not have a good ventilation system, or the outside temperature is very high then the loss of long-wave radiation is not as critical
- light diffusion must be enhanced. Generally, plastic films that diffuse light have lower transmission of visible light than clear plastic. In sunny climates it better to have optimum light distribution that avoids shadows, and provides ample radiation to all plants rather than a greater total amount. Where the radiation climate is poor, this may not be the case because much of the incident radiation will be diffuse due to clouds
- ultraviolet transmission is also important. Part of the UV radiation is necessary for fungi sporulation. If the covering functions to filter critical wavelengths, by reducing transmission
into the greenhouse, this will control the incidence of disease and the need for chemicals. Such filtering must be very precise because if it impedes desirable UV radiation adverse effect can arise (such as the thriving of beneficial insects that require UV radiation or the excitation of some phytochromes that affects the colour of flowers)

**Water and precipitation**

Obviously rainfall does not enter the structure directly because of the coverings, but is important to avoid the possibility of water ingress. It is necessary to carefully regulate water supply and humidity internally. A regulated water supply is essential for indoor agriculture. Hand watering is acceptable for some greenhouse crops if labour is available when the task needs to be done; however, large areas cannot be managed this way, and the water use efficiency is poor with hand watering. A variety of automatic watering systems are available that can manage water supply for a wide variety of plant materials, containers, and soil mixes that need different amounts of water. Time clocks can be used where the climate is regular and there are few meteorological surprises. Mechanical evaporation sensors can be used to control automatic watering systems where there are significant day-to-day variations expected. Mist sprays can be used to create humidity or to moisten seedlings. Watering kits can be obtained to water plants in flats, benches, or pots. The exact watering requirement is dependent not only on the climate and the internal control system, but also on the soil or growing medium. The growing medium has to be watered when dry. Over-watering in a climate-controlled greenhouse environment can cause plant or seedling death. Drip irrigation systems are effective - they prevent leaves from getting wet, and are gentle on seedlings. Sensor control of watering can also be achieved by soil water tensiometer to trigger spray/mist/drip only when the soil gets too dry. Care has to be taken to prevent too-large fluctuations in the soil water content that may adversely impact on plant growth. Finally, good drainage is another requirement for the site. When necessary, the greenhouse should be built above the surrounding land so rainwater and irrigation water will drain away.

**Temperature**

The temperature range for crops grown indoors is similar to that for crop grown outdoors. The important aspect of temperature is the chance to control it inside the greenhouse which results in a better product, timed to be most valuable, which is not possible with conventional outdoor agriculture. Temperature is very important in controlling agricultural yields as regulated by photosynthesis. There is an ideal temperature range that can be maintained inside a greenhouse in order to grow a high quality, large quantity product. Temperature control also reduces the need for agrochemical products.

**Humidity**

The excess or deficit of relative humidity is very important for optimum plant development. A deficit provokes high looses of water from the plant trough the transpiration and can create condition for pest infestation. If low humidity remains for a log time plants can suffer hydric stress which can be an irreversible process resulting in the death of crop. Excess humidity can be controlled by ventilation systems. Such control is essential to prevent the infestation of fungi or bacterial diseases in the greenhouse. A deficit or excess of humidity will lead to increased costs by the additional use of agrochemical products and the possibility of loosing all production of a particular crop.

**Wind**

When designing a greenhouse, wind is one of the most important factors. The natural wind climate must be taken into account. The wind speed and direction is important for
choosing the best place (avoid high winds than could damage the structure and/or coverings). The wind is also used in simple greenhouse designs to maintain the thermal balance by taking advantage of its prevailing speed and wind direction. Wind ventilation can be used to: balance temperature internally by circulation of air retained between the roof and the plants; reduce relative humidity; pollinate plants; and replenish oxygen and carbon dioxide for the crop.

### 3.3.2 Meteorological requirements and limitations

There are no specific meteorological requirements for indoor agriculture. The climate influence supersedes most meteorological influences. There are three specific meteorological limitations that must be considered: snow, hail and wind.

**Snow**

The effect of snow is by the accumulation of mass on the structure. For the example structure in Figure 4, there is a roof area of 140,400 cm$^2$. If we assume an inch of snow (2.54 cm), this would be 356,616 cm$^3$ of snow accumulated on the roof of the greenhouse. With an assumed density of 0.12 g cm$^{-3}$ this would result in an additional mass of nearly 43 kg to be supported. For a small structure as in the example, this is perhaps not critical, but for an extensive structure as illustrated in Figure 2 this would be a problem unless the shape was designed (as in this case) to shed snow by gravity. The impact of snow in climates where significant falls are likely can be accounted for in the structure design (Figure 3), but in climates where snow is less common (e.g. mid-latitude, European, temperate maritime) the occurrence of unusual snow events should be considered when siting and designing a structure.

**Hail**

The impact of hail damage (Figure 7) cannot be over-emphasised. Most greenhouse coverings are now designed to withstand hail storm effects, but there is much evidence that severe storm events will damage materials that are guaranteed for up to 10 years. As with snow, there is a more general climate influences to consider; what is the risk of a severe event? The bigger problems is perhaps likely to occur in areas where severe events are not commonplace. The use of radar to detect and provide early warning of severe events is a service that could be useful from two perspectives: that of trying to cover the structure with a temporary protective material, and ensuring personnel are not inside during a storm and maybe exposed to flying glass or other dangerous materials.

**Wind**

In North Carolina, a winter storm in March 1993 caused over $5 million in damage to farm structures, mainly greenhouses. The damage was caused by both wind (in the eastern part of the state) and snow (in the west). It was found that the main cause of the wind damage was inadequately built foundations (i.e. catastrophic failure of the whole structure, not just the covering). There are two specific approaches to dealing with wind that are available. If the structure is permanent and long-term both should be applied. The first option is a wind break (Figure 8) planted to protect against prevailing winds. Care has to be taken to avoid shading, dirt accumulation on the structure, and the risk of the windbreak actually damaging the greenhouse. The second option is
to use deeper foundations during the installation process. The wind-break is the only practical option for post-construction remedial action.

![Diagram of wind flow through and over a protective screen]

**Figure 8**: The design and operation of a wind break for greenhouse protection

### 3.3.3 Land requirements and suitability

The site chosen for indoor agriculture should have a soil with good drainage, good fertility (correct pH, an equilibrated content of nutrients and enough organic material, if crops are to be sown directly; use of a growing medium means soil limited land can be used), perfectly level, homogeneous texture, good depth, and not prone to weed, pest and disease infestation.

**Terrain and slope**

A perfect level site is preferable. A maximum gradient of 2-5 m /1000 m means that excessive engineering costs during construction will not make the investment too large. A stepped terrain results in large temperature variations over the site (1 to 5°C during night and 10 to 15°C during the day) which will have a major influence on the production management that is definitely undesirable. The problem with flat sites is the risk of flooding. To avoid this it is necessary to install very efficient under-ground drains. These usually comprise of perforated PVC filled with fine sand (<0.15mm) and coarse sand (>0.2 mm), to permit a good drainage.

**Soil**

Where crops are to be grown directly in the ground, the fertility characteristics of the soil are important. It is necessary to obtain a nutritional balance between macro nutrients (N, P, K, Ca, O, H, S, C and Mg) and micro nutrients (He, Cu, Mn, Bo, Mb, Co, and I). The exact balance is crop-specific. The incorporation of organic material (around 5% by weight) is preferable for vegetable production because of high decomposition rates by micro organism. Organic matter incorporation should be started at least one year before the first crop sowing. A dose of 4 to 5 kg m⁻² of dung, or 2 to 3 kg m⁻² of peat will provide stable soil structure, thus permitting a good oxygen and water balance, good water retention, and active micro-organism community and suitable cation exchange capacity.
Foundations and Floors

Permanent foundations should be provided for glass, fiberglass, or the double-layer rigid-plastic sheet materials. The manufacturer should provide plans for the foundation construction. Most home greenhouses require a poured concrete foundation similar to those in residential houses. Quonset greenhouses with pipe frames and a plastic cover use posts driven into the ground.

Permanent flooring is not recommended because it may stay wet and slippery from the growth medium. A concrete, gravel, or stone walkway 0.6 to 1.0 m wide can be built for easy access to the plants. The rest of the floor should be covered by several inches of gravel for drainage of excess water. Water also can be sprayed on the gravel to produce humidity in the greenhouse.

Water status

Maintenance of good water status is more important for indoor agriculture than conventional production because it relies on the production of premium product. Important considerations related to water status are: (i) the water quality – the salinity level; (ii) the temperature – which will effect microclimate regulation and fertiliser function; (iii) quantity – the evapotranspirational demand and drainage (closely related to specific crop requirements) dictate the volume of water required to maintain water availability to the crop; (iv) availability - the water storage in the soil and on a larger scale, the total supply of water to the indoor production system (rain-fed, ground-water, stream water); and (v) the distribution method (irrigation system) – how the water is made available to the crop.

Irrigation and fertilisation are commonly managed in tandem with a process known as "fertirrigation". This activity tries to spread the water and nutrients uniformly, under controlled conditions by using water mixed with liquid fertilisers. The system has the advantages that absorption by roots of vegetables is facilitated, there is reduced risk of soil salinity build up due an accumulation of salts contained in fertilisers, water loss by infiltration is reduced, more efficient use of the work force is possible and control of soil pH can be achieved.

Land suitability classification and specification

There are few specific land suitability issues related to indoor agriculture with the exception of the land needing to be level and not being subject to severe topographic temperature gradients. Where direct to soil planting is to be used, the following is a draft recommendation of a desirable soil:

- good water holding capacity (but off-set somewhat by the advantages of lighter soils)
- at least 75 cm depth
- sandy (heavy soils make disease management difficult)
- pH between 6 lightly acid to 7.5, (extremes of pH can result in nitrification, disease control problems, He, Al and Mn toxicity and low Cu and Ni availability. It is possible to control pH by use of peat, compost, manure and burnt lime stone)

3.3.4 Pest and disease management

Greenhouses permit the control of temperature and relative humidity. These factors are important with respect to the presence of pests and diseases. Some structure characteristics help to control these problems. Other options are meshes, traps, and the application of Integrated Pest Management. In general, indoor agriculture makes pest and disease management more effective because the confined space makes wind-borne infection
less of a problem, the microclimate can be controlled to be unfavourable for the pest or disease, and the crop can be easily sprayed in a targeted manner.

3.3.5 Environmental extremes and risk

The major risk for indoor agriculture is the risk of severe storm events with associated high winds, snow and hail (see section 4.3.2)

3.4 DATA AND MODELS

The using of crop growth models is quite widely applied for the management of field crops. Its application to greenhouse crops is also well developed but perhaps under-used. In some cases it may be impossible to apply a particular outdoor crop model (such as those designed for large (macro-scale) areas, or empirical models) to indoor production. The controlled environment in a greenhouse means that data availability is less of a problem that for a farm field, and the prediction of future conditions is quite reliable because temperature, humidity, and nutrient supply can all be controlled. The only non-predictable factor may be radiation (and that is unlikely to vary greatly outside climatic norms). In addition, poor natural radiation can be supplemented by illumination if there is a significant cost-benefit. The output quality from crop models is usually quite reliable, provided that the model has been calibrated and validate for the local conditions.

3.4.1 Data availability and resolution

The data required for models are the time series of input variables and initialisation parameters. The variable time series are needed to drive the model. The model should use growth integration, variable in time, specific to a crop and the variety. The exact requirement is model specific, but for an controlled greenhouse, humidity, temperature and water input data should be available on a sub-hourly basis for each compartment of the structure. This is a significant advantage compared to field production when it comes to dynamic simulation modelling.

3.4.2 Specification of "ideal data"

It is not possible to determine the "ideal data", but a draft "minimum data set" can be specified. Based on models like "CERES" and "CROPGRO" (sponsored by FAO), the minimum information required to run a simulation model for a greenhouse would be:

1. Soil properties as a function of depth: horizon thickness, upper and lower limits of volumetric water, volumetric water at saturation, bulk density, pH, organic carbon, total nitrogen.
2. Daily weather data: radiation, precipitation, maximum and minimum temperatures (a greenhouse can permit a much greater temporal resolution)
3. Crop parameters: maturity type, photo-period response, yield components
4. Initial conditions: water content by depth, nitrates and ammonium by depth
5. Management conditions: sowing date, plant population, irrigation amounts and dates, fertilizer amounts and dates, residue management, ploughing depth

With regard to evapotranspiration, there are various requirements depending on the method used to calculate this parameter (Penman - Monteith, Priestly - Taylor, Linacre, pan evaporation,...):

- Penman-Monteith (model vapour diffusion and energy budget): **parameters**: height above canopy of wind speed measurement; short-wave absorptivity of leaves, resistance of canopy when stomas open, aerodynamic resistance of the canopy, latitude; **data**: wind speed, min/max air temperature, solar radiation, relative humidity, saturated vapour density (can be estimated from air temperature if not available); simulated variables: height of canopy
Priestly-Taylor (simpler version of Penman-Monteith, does not simulate aerodynamic resistance to vapor transport): parameters: alpha, short-wave absorptivity of the soil surface, latitude; data: minimum/maximum air temperature, solar radiation; data or simulated variables: cloudiness

Pan (based on direct measurements of evaporation): parameters: pan and crop coefficients; data: daily measured pan evaporation

Linacre (simple empirical formula based on easily-obtainable data): parameters: elevation above sea level, latitude; data: minimum/maximum air temperature, dew-point temperature (optional, minimum air temperature can approximate this)

The data used should be viewed with caution, and verified both theoretically and practically before application with a model.

3.4.3 Agricultural production models

Crop growth models are computer programs that integrate information on daily weather, genetics, management, soil characteristics and pest stress to determine daily plant growth and subsequent yield. They are applied to different areas such as plant breeding, planing, research and directly in decision support systems for improving farm management.

Two kind of general models ICEMM and GOSSYM are used to show how such models work:

"ICEMM can be subdivided into two subsystems: the above-ground (primarily plant physiological) and the below-ground (soil) processes. The major subroutines are:

- CLYMAT – reads all the weather information and calls the subroutines that keep track of the time (DATES) and that calculate the soil temperature (TMPSOL);
- SOIL – the controlling program for all the soil subroutines;
- PIX – estimates the reduction in growth due to the application of Mepiquat Chloride (PIX);
- PNET--calculates the photosynthesis rate/dry matter production;
- GROWTH – calculates potential and actual daily growth rates of each of the organs on the plant including roots (RUTGRO);
- PHENOL – simulates plant morphogenesis and abscission of leaves and fruits (ABCISE) and fiber quality (QUALITY);
- PMAPFL – adjusts fruit load and plant height as a result of plant mapping.

The SOIL subroutine is basically derived from the 1973 work of Lambert and Baker known as RHIZOS. It consists of the following subprograms:

- FRTLIZ – initializes nitrogen and organic matter content of the profile at planting and distributes applied fertilisers in the profile;
- GRAFLO – moves the water into the profile after a rain or an irrigation event by gravitational flow and moves nitrogen in solution by mass flow;
- ET – estimates evapotranspiration;
- UPTAKE – calculates the amount of soil water taken up from the soil region where the roots are present;
- CAPFLO – rewets the soil by capillary flow in response to soil moisture gradients and moves nitrogen by mass flow;
- NITRIF – calculates the mineralization of organic matter and urea and the nitrification of ammonia;
- RUTGRO – calculates the potential and actual growth of roots and average soil water potential, and calls RIMPED, which estimates the effects of bulk density on the capability of the root to elongate; and
- TMPSOL – calculates the soil temperature by layer. A spatial description of roots, water, nitrogen and temperature is achieved through the use of two-dimensional geometry".
GOSSYM simulates the plant's response to environmental factors as follows: canopy light interception depends on light intensity. Respiration depends on temperature and plant biomass. Growth is a function of temperature, tissue turgor and metabolite supply. Thus, the plant water status is a determinant of both supply and demand for metabolites. Water stress reduces photosynthesis, transpiration and nitrogen uptake. It also reduces growth and the demand for nutrients. The supply/demand ratios for carbohydrate and nitrogen are used as indices of stress-induced time delays for morphogenetic events. It is assumed that the metabolic supply/demand status of the plant determines hormone balances which alter morphogenetic rates. This status also determines or shifts the balance in the hormone system which results in the abscission of fruits. Therefore, while the morphogenetic rate is driven by temperature, it is affected indirectly by those factors determining the supply and demand for carbohydrates and nitrogen. Severe moisture stress and a heavy soil may combine to stop new node formation, while a mild moisture stress which reduces growth more than it reduces carbohydrate supply may have no effect on new node formation or may cause a relative increase in the morphogenetic rate."

A major issue with simulation modeling is the large number of model parameters (calibration values) and input data that are required. The question naturally arises: what happens if we get some of these wrong? The correct question is: how sensitive is the model to variations in parameters or data? Especially since parameter calibration is seen by some as little more than a "black art". Sensitivity analysis allows us to see where we should concentrate our calibration and modeling efforts, i.e., where the model is most sensitive.

Some definitions are necessary to understand all the things that are involved in model sensitivity:

- sensitivity: rate of change in output variable per unit change in input variable or parameter.
- absolute sensitivity: in terms of units, e.g. 'kilograms of yield' per 'mm of precipitation'.
- relative sensitivity: both factors standardized to zero mean and unit standard deviation.

A basic method for sensitivity analysis adjusts parameters in a predictable way, runs the model for the range of adjusted inputs, and records the output. A plot results vs. parameter value, with regression analysis to quantify the effect of the parameter on the results provides an indication on sensitivity. The absolute sensitivity is the slope of the regression line. The relative sensitivity is the slope of the regression line if both the independent and dependent variables are standardized; this is the correlation coefficient.

The question that arises from this method is how to vary the input parameter in a meaningful manner? There are a range of methods:

- Method 1: random sample from a known or assumed probability distribution. This gives an unbiased estimate of the sensitivity to the parameter, if the underlying distribution is known.
- Method 2: random sample from a known or assumed empirical distribution (e.g. historical time series)
- Method 3: non-random sample from a known or assumed probability distribution, selecting ±1, ±2 standard deviations. This is an efficient way to get the sensitivity to extreme values of the parameter.
- Method 4: stratified random sample from either a probability or empirical distribution. This sampling scheme has certain desirable theoretical properties that allow an estimate of sensitivity with a smaller sample size because the sample is more evenly spread out over all possible values. An example of this approach is Latin hyper-cube sampling (LHS)

The issues of synergism (interaction between parameters) should also be considered.
In general, the application of models to indoor agriculture problems should be more straight-forward than for field production because conditions are predictable (and measured in many cases), and there is potentially less spatial variability (if soil is excluded and other, more homogeneous growing media are employed).

3.4.4 Knowledge gaps

In many countries of the world, it is normal nowadays to use dynamic simulation models for many management purposes. Application of crop growth models under greenhouse cultivation is not a common practice, perhaps because outcomes are very predictable. There are however a range of potential uses for management support and market timing that make models an attractive tool for the producer. It will be necessary to make some modifications to, and to calibrate, crop growth models designed for simulation of field cultivation situations before applying to greenhouses. However, there is an increasing range of indoor-specific models available.

Agriculture under the controlled conditions of protective structures is an advantage for modelling because the number of variables is reduced compared to field agriculture, and the spatial complexity is reduced. It is imperative that collaborative work between researchers, model developers and users is encouraged. Specialised development teams would allow the sharing of experience and knowledge to improve protected cultivation. The general use of models would lead to improved quality (of models and product), standardisation, portability and flexibility (of models).

The number of inputs necessary to run dynamic simulation models ranges from 10’s to 1,000’s of parameters. Where spatial variability can be ignored, the numbers are less. Each of these must be established by calibration or from "first" principles. The big problem is that experiments rarely give information on multiple parameters, and most of the possible interactions are unknown. Also, for some models, many combinations of parameters can lead to the same final outputs thus leading to confused interpretation. What is needed is insight into the physical system, and again many of the interactions are poorly understood. For example, calibration of the CERES and CROPGRO series of models for the IBSNAT project required very large and detailed experiments lasting many years, and even now it is unclear how to adjust the model for a new location without some local insight.

The complexity in water uptake and transpiration in crops models means that it is necessary to improve precision and experimental observations within the greenhouse. Identifying solar radiation and vapor pressure deficits (that lead to stomatal reactions) and the relationship between humidity and transpiration for various locations within a structure will be necessary. Such knowledge will lead to information about the amount of additional water or energy to be supplied to specific locations within the greenhouse. Canopy development is also different with protected cultivation. In some conditions the leaf index area (LIA) is greater, and in other conditions is smaller. This vegetative development is closely related to photosynthesis and yields.

3.4.5 Available decision making and knowledge management tools

Apart from the widely available crop growth simulation models already mentioned in this, and the other chapters of this document, there are a number of greenhouse specific models of crop growth.

Hortisim is a mechanistic simulation model of C3 greenhouse crop growth and its interrelationship with the greenhouse climate. It calculates photosynthesis, dry matter production and transpiration for an average crop (assuming a closed or a row canopy) and the dry matter production and dry matter partitioning of indeterminate vegetable fruit crops (tomato, cucumber, sweet pepper, melon). It quantifies the energy, CO₂ and water use. This range of
The benefits of using these types of decision support tools are:

- reduced in pesticide use (by 80%-90%, or even complete elimination)
- reduced in fertiliser use (by 40% to 80%)
- a healthier work environment and greenhouse ecosystem
- computerised greenhouse management database
- presentation of management information in a variety of forms: pictures, tables, graphs, text
- provision of a common, central decision-making process (to avoid conflicting recommendations)

### 3.5 INTERACTION WITH THE AGRICULTURAL COMMUNITY

#### 3.5.1 Dissemination of information

Traditional dissemination by agricultural advisers and farmer interaction is common in the indoor agriculture community. In a similar manner to machinery manufacturers in arable production, the producers of infrastructure (frames, coverings, climate control systems) are also responsible for disseminating the latest information to producers. Information networks hosted on the Internet are widely available for those active in indoor agriculture (e.g. Farm Business...
Management Information Network; Global Agribusiness Information Network; Nursery Resources). There is a large body of information available regarding planning, design, crop selection, harvest, pest-control and other aspects of production that any prospective farmer can review.

3.5.2 Typical end users and their perceptions

It is impossible to say what the typical end-user is like, but the relatively high capital investment, and the long-term integration of technology means that producers must tend towards being technophilic, and must be willing to rely on scientific information. Users are likely to be willing to accept decision support tools and management models because they will want to get the most out of the technology available to achieve the best gross margins.

3.5.3 Potential gains of using agrometeorological data

The adequate use of agrometeorological data is fundamental to greenhouse management. The monitoring of meteorological and agricultural factors helps to improve yields, quality and quantity of crops. It is necessary to take control of at least temperature and relative humidity as these are the principal factors in greenhouse production. Unlike field production, where access to reliable data is poor, there are many unknown variables, and great spatial variability (in soil, topography, plants and weather) in indoor agriculture the necessary data for using models is much more easily obtained. Even if a producer is not using a model, access to weather forecasts will allow for planning of energy consumption and infra-structure protection. Agrometeorology will play an important role in planning where most benefits can be gained from indoor agriculture, the design of structures and the on-going management of internal climate.

3.6 SUMMARY OF FINDINGS

term of reference a)

To define properly the mentioned fields of agricultural production:

Indoor agriculture is a production system that uses protection structures for growing plants, usually with plastic or glass coverings, to avoid or lessen the effects of abnormal weather. The system helps to conserve heat and to maintain a favourable water, temperature and humidity environment for growing and developing plants which results in better harvests (i.e. it is possible to get more production per area). Depending on the crop, its handling and the optimum combination of many variables, the yields can increase between four and twelve times that normal obtained without protection. This can lead to better food security and can give better products for domestic and international markets.

term of reference b)

To determine the most important agrometeorological and agroclimatological aspects of the mentioned fields of agricultural production:

- protection against adverse climatic conditions, such as hailstorms, excess rainfall, strong winds and frost
- cultivation of areas where some years ago it seemed impossible to produce viable crops
- control of many microclimatic factors: temperature, humidity, UV light, diffuse radiation, water availability
- shelter against adverse climatic conditions, at the same time provision of an environment adequate for maintaining plants in good conditions
- maintenance of temperatures at those required for optimum plant growth
• ventilation requirements vary with the climate, the current weather, the season, and the use for the greenhouse. Integrated automatic control systems should be compatible with the local climate
• Infrastructure damage by hail snow and wind

term of reference c)

**To determine the most important management aspects in the mentioned fields of agricultural production that have agrometeorological and/or agroclimatological components:**

• choosing coverings based geographical location, the maximum, minimum and average temperatures, the possibility of frost, the wind climate, relative humidity, rainfall distribution and intensity, solar radiation and the crops that are going to be grown
• as a general rule, each covering layer reduces light by about 10 percent (about 80 percent of the light filters through double-layer plastic, compared with 90 percent for glass)
• the colour of these films variable from white pearl (milky) to lightly yellowish-green; the latter are recommended for cloudy and rainy climates (referring to types of covering)
• the best environmental conditions for production
• the choice of market condition of the produce
• the choice of timing of harvest for maximum return
• regulation of internal conditions (temperature, humidity, radiation, air-flow)
• climate parameters must be managed: a) radiation: visible light transmission for plant photosynthesis; b) rainfall: regulation for water use efficiency and disease management; c) temperature: control inside the greenhouse; d) humidity: excess or deficit important for the plants development and disease control; e) wind: important when designing a greenhouse, and to maintain thermal balance by taking advantage from the speed and wind direction.

term of reference d)

**To review conditions and measures to optimise agricultural production in the mentioned fields where agrometeorology can play an important role:**

• the adequate use of agrometeorological data is fundamental in the greenhouse management, the monitoring of meteorological and agricultural factors helps to improve yields, quality and quantity of crops. It is necessary to take control at least of temperature and relative humidity, these are the principal factors in greenhouse production.
• agrometeorology will play an important role in planning where most benefits can be optioned from indoor agriculture, the design of structures and the on-going management of internal climate

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CHAPTER 4

PRECISION AGRICULTURE

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4.1 WHAT IS PRECISION AGRICULTURE?

4.1.1 Scope

Precision agriculture is known by a number of names. Synonyms include precision farming, site specific farming, site specific crop management, targeted agriculture and prescription farming. These all have the same concept behind them, which is to only use what is needed where it is needed, rather than the more conventional approach of using a uniform, blanket application of each input. Precision agriculture can be defined as: "the use of information and information technology to make and implement management decisions at the appropriate scale" (Holden, 1999). In this definition, information is any fact or data that describes the farm (soil, slope, drainage, yield etc…), information technology is the tools used to manage information (computers, software, sensors, computer controlled mechanisation systems), and scale is the physical extent of the land to which management is being applied (farm, field, within-field, plant etc…). NRC (1997) similarly define precision agriculture as "…a management strategy that uses information technology to bring data from multiple sources to bear on decisions associated with crop production." Precision agriculture is generally thought to imply responding to sub-field scale variability. The ideas, technologies and techniques are applicable at any scale; the methods used and the technologies employed vary from site to site while the underlying concept remains the same. Chris Johannsen (Purdue University) defines precision agriculture as "…carefully tailoring soil and crop management to fit the different conditions found in each field" (http://pasture.ecn.purdue.edu/~mmorgan/PFI/over.htm). This definition is fully compatible with the ones above, and it is worth noting that neither of these definitions assumes the use of any specific technologies or management strategies, rather they describe a concept that uses modern technology to enhance farming. The use of sensors (soil properties, yield, weather etc…) in conjunction with a Global Positioning System (GPS) means that geo-referenced data (a value describing a physical property with an associated position coordinate) can be managed in a geographical information system (GIS), integrated with system models, and used to predict the best course of action for a field (the resulting control information being known as an application map). Variable rate technology (VRT) is then used to implement the application map by applying only what is needed, where it is needed. From this we can conclude that precision agriculture is a suite of technologies that enable tailored soil and crop management at the appropriate scale for optimum agricultural efficiency. The farmer picks and chooses from the available technologies in order to achieve the best performance from the land with the minimum environmental impact. Schueller (1997) summarised the technologies required for precision agriculture and discussions of the basic concepts are to be found in NRC (1997), Lake et al. (1997), Fuller (1997) and John Deere Publishing (1997).

Precision agriculture operates as a cycle (Figure 1). The farmer starts by collecting data, which will usually be in the form of a yield map, and probably more detailed soil and environmental data. This is then interpreted to create application maps for management of the production stage, and the result quantified in the next
year’s yield map. The idea is that as more and more data are collected, better informed decisions can be made about how best to manage the farm.

To achieve the full potential of the system data has to be accumulated over a number of years. Guidelines vary, but in general at least three years of data are needed to identify temporally stable trends in crop performance before thinking about using variable rate technology (VRT). A period of at least 5 - 7 years is required to make a full transition to precision agriculture. It is however possible to use elements of the system (such as real-time sensor controlled targeted spraying, interpreted yield maps, and geo-referenced soil sampling) from the outset.

One of the possible consequences of using precision agriculture for farm management, particularly with reduced inputs via VRT, is that the risk buffer created by blanket applications might be removed, thus making life more difficult for the farmer. The risk buffer is created by using more inputs than needed to guard against the unexpected, or to ensure a minimum return, even if it is not the optimum return. It is reasonable to state that many farmers like to be sure of achieving a certain return, even if it is not the best possible, rather than gambling on a larger return that may mean loosing everything. The fact that risk is not yet fully understood and integrated into precision farm management concepts would seem to be especially troubling for small family farms. Welsh et al (1999) found that trying to use a yield map to manage nitrogen application had significant consequences for yield the following year, with a reduction of 0.9 t ha⁻¹. Until the risk of such an outcome is reduced then variable rate management will not be adopted. The biggest factor that makes the lack of a risk buffer important is the weather. In a bad year (or cycle), it is possible to loose more using precision agriculture than conventional farming (based on current knowledge). It is very important that meteorological tools are developed for precision agriculture over the next few years as this is one area of its development that is not properly understood at the present time (2001).

4.1.2 History

Historically, with the beginning of agriculture, and still in parts of the world today, farmers plant seed by hand, and tend to each plant individually. The farmer's care of the plant depends on how it develops and grows. By such careful attention, farmers come to know in great detail the variability within their fields. With the introduction of animal power, and then mechanisation systems, this precise management decreased and areas of land started to be treated in a uniform manner that enabled a good average return. Up to about 100 years ago, when farmers in the western world still relied on limited mechanisation, they had small fields that were relatively uniform. As power and machinery increased fields were made larger to allow better machine efficiency. The cost of this was to reduce the precision of plant management, and uniform inputs to the system were increased to ensure a good, economic return. It was soon realised that from the farmer's point-of-view, improved productivity from mechanisation outweighed any loss due to less plant specific management.

Over the last 75 years or so of mechanised farming there have been many land managers who realised that they could get an even better return, potentially for less cost, if they targeted input based on variation within the field. In the last 20 years technology has finally matured that permits farmers to do just that. Developments in computing, miniaturisation, electronics, sensing, positioning and machinery technology allowed "precision agriculture" to emerge. Initially the ideas were developed on the Great Plains of the USA where extensive grain production facilitated its application, and it is in the area of cereal production that there has been most technological development. In recent years sensing technologies for root crops and grassland agriculture have been developed, and the principles have been applied in orchards and on plantations. It is now reasonable to say that precision agriculture can be applied to any farming enterprise to some extent.

Due to the reliance on technology precision agriculture tends to be conceived of as being only relevant to big farmers or plantation managers. This need not be the case, it can be
argued that the analytical use of information is applicable to all farmers, and technologies to vary management within a field can be made low tech. However developments in this respect will have to be local because the large machinery manufacturers that are pushing precision agriculture in Europe, America and Australia have little interest in areas with less mechanised agronomy.

Robert (1999) presented an analysis of a survey of precision agriculture researchers compiled from questionnaires at an international conference in 1998. He found that the vast majority of those attending the conference considered engineering technology to be the most important research area in precision agriculture. In fact it is noticeable that the role of weather was not considered a research issue at all. A review of papers presented at international conferences over the last 5 years reveals very little interest in the matter of weather and its influence on in-field spatial variability. It most commonly arises as an issue with regard to insurance claims and risk management products. As a source of in-field spatial variability, micro-climate has received little or no attention (with a few notable exceptions discussed later). The lack of interest to date makes it very difficult to analyse what agro-meteorological tools would be useful for assisting precision agricultural management, and even what information is likely to be most useful to the farmer or agronomist.

4.1.3 Rationale and goals of precision agriculture

The generally accepted rationale of precision agriculture is that with currently available technology, it is possible to match inputs and management at a sub-field scale in a site-specific manner without sacrificing mechanisation efficiency. Thus the farmer gains the productive benefit of large field mechanised crop production and husbandry on a much smaller scale. If we move away from the concept of high-tech. and expensive equipment, the rationale becomes to use as much information as possible in a consistent and controlled manner to achieve the most efficient management of the farm at appropriate scales.

The goals of precision agriculture can be defined as:

(i) **optimum production efficiency** - to produce high quality crops with as little waste of energy and inputs as possible. This does not mean getting the most crop from the field. An inherent assumption of precision agriculture is that those areas that are poor yielding will either be managed to increase yield or to some extent omitted from production. This means that total yield from a field may in fact drop, but the efficiency of production for the field may increase thus improving the gross margin.

(ii) **economic efficiency** - one of the most common tools used to illustrate the benefit of precision agriculture is the gross margin map. In its simplest form the gross margin map mirrors the yield map. It is calculated by subtracting the cost per unit area of field from the value of the yield at a given location (based on the same unit area). If the field has uniform management it is possible to see the economic efficiency of production. If a complete variable management history cost map is built up then the economic efficiency of a fully variable-rate system can be estimated.

(iii) **minimisation of risk** - the risk that a farmer faces is one of the biggest issues in the social and mental welfare of the enterprise. Risk can be evaluated and is usually regarded in terms of agricultural economics, not in physical terms. The agricultural economist considers tolerance of risk, and how farmers choose to manage risks. Risks can be handled in one of five ways (Risk Management Agency, 1997): (i) **retain** - no protection from downside risk, as in holding an unpriced commodity. For many smaller farmers and those in the less developed parts of the world this is the only option, therefore any agricultural management system must minimise all possible risks. (ii) **shift** - insuring against risk. The more risk is shifted, the higher the cost. This approach is not readily available in Europe and is unavailable in many parts of the world except North America. (iii) **reduce** - best management of the land,
i.e. trying to do all the correct things. For the vast majority of farmers this is the only viable approach to risk management. (iv) *self-insure* - emergency reserves funded from previous years’ profits. This is only available if a profit is made. (v) *avoid* - limiting all management decisions to ensure there is as little risk as possible such as not pushing either end of planting windows or not increasing debt-to-asset ratio beyond a comfortable level. For the vast majority of farmers option (ii) is not available and option (iv) cannot be relied on, therefore there is a tendency to fall between options (iii) and (v), i.e. keep the risk to an absolute minimum. The question farmers have to ask of precision agriculture is whether risk is minimised? It is reasonable to treat risk minimisation as a goal of precision agriculture, but it may well not be a consequence.

(iv) *limit the impact of agriculture on the wider environment* - this is somewhat analogous to economic risk in that farmers have an increasing obligation to protect and preserve their working environment. From the developed world point of view this may be driven by society (as reflected for example in European environmental legislation), while elsewhere it is the best means of ensuring the continued successful running of the enterprise.

Harris (1997) concluded that precision farming might play a role in helping a farmer manage the technical risks of the enterprise provided that yields are maintained at a suitable level to withstand both financial and weather fluctuations.

If production efficiency is optimised then it is reasonable to assume that the economics will follow, but that may well incur unacceptable risk for the farmer. Demonstrated quantified environmental benefits are difficult to prove. Currently it is assumed that if there are less inputs in the system then there must be less waste (which seems reasonable). It is quite clear that weather has a substantial role to play in determining the success or otherwise of using precision agriculture for farm management, either in terms of the crop’s ability to withstand the weather that influences it in a given season, or in terms of the yield and economic success of the farm.

### 4.1.4 Major crops produced

The majority of developments in precision agriculture have started with grain or cereal crops in mind. The use of information technology and spatial data can be applied to any farming enterprise, but for full benefit a yield map must be constructed, therefore a yield monitoring system is required. Yield meters are at various stages of development, but to date monitoring is established commercially for grain, cotton and potatoes. Any combinable crop can be yield mapped (corn, maize, wheat, oats, barley, sorghum, rice) (Whelan and McBratney, 1997; Iida *et al.*, 1998; Thylen *et al.*, 1999; Jürschik *et al.*, 1999; Stafford, 1999), and any relatively clean and graded crop that is processed via a conveyor (potato) (Ehlert, 1999). Cotton (Searcy, 1998; Perry *et al.*, 1998; Boydell and McBratney, 1999) and peanut (Durrence *et al.*, 1998) monitoring is now becoming established and there are methods available for beet crops (Wheeler *et al.*, 1997; Hall *et al.*, 1998). Yield mapping forage crops is still somewhat experimental due to the need to sense dry matter, but developments have been made in precision viticulture (Tisseur et al., 1999). The construction of yield maps from tea plantation records has been recently investigated which clearly illustrates that a high-tech. mechanised approach is not needed to apply precision agriculture concepts. Sugar cane is another plantation crop that is being looked at as suitable for precision agriculture technology (Saraiva *et al.*, 1999), while the high value of tomatoes has also attracted attention (Pelletier and Upadhyaya, 1998).

### 4.1.5 Geographical occurrence

Precision agriculture has a foothold all over the world to a greater or lesser extent. It is however safe to say that it is most prominent in developed countries or where particularly
valuable plantation crops are grown. The commercial adoption of precision agriculture has been limited to some extent by the fact that the promised benefits have not materialised as quickly as expected. This can perhaps be accounted for because the magnitude of multidisciplinary science needed to understand farming systems at a sub-field scale is huge. The influence of weather is one area which has been subject to very little research. In general research institutions are leading the initial adoption of precision agriculture, but there has been very little thought put into how the ideas and principles can be applied to small farm units. The focus is predominantly on large land holdings, high value crops and technologically educated users.

Africa
Due to education and small farm sizes precision agriculture is not widely used in Africa, but where high value crops are grown (e.g. tea) the principles are being adopted, such as using manual logging of tea picked to produce yield maps. There is some research starting on low-tech variable rate technology suitable for small farmers (e.g. Kebede et al., 2001) but the agronomic developments needed to support the machinery have not been developed yet.

Asia
The commercial significance of precision agriculture in Asia is currently not very great, but there are an increasing number of farmers adopting component technologies. According to Srinivasen (1998), Asian farmers are reluctant to adopt new technology, and a lack of clear success by precision farming has meant adoption is slow. It is also apparent that technological ignorance makes adoption more difficult. For farmers to want precision agriculture they must have a suitable technological education. Developments still tend to be at research level with much technological advancement coming from Japan, but in areas where high value crops are grown on a large scale (orchards in Thailand; cotton, tea and coffee in India) some commercial efforts are being made.

South and Central America
In Brazil there were about 50 combines with yield mapping operational in 1998/9, and the number is increasing. There are a number of farmers keen to adopt if the benefits are clearly shown. Elsewhere developments are still at the research stage such as development of a GPS controlled fumigation systems for bananas.

Europe
Precision agriculture in Europe is staring to be used commercially in most countries for crops ranging from cereals through root crops to orchards. GPS control of spreading operations and computers as part of farm management are increasingly common; both of which are component technologies of precision agriculture. The benefits of adoption need to be more clearly demonstrated before it becomes a “common” management method. Its use is most prevalent where large land holdings are common. In countries with smaller farms there is a marked reluctance to adopt. There are some indications that precision agriculture technologies will become common for licensed nutrient spreading and nutrient management planning applications for environmental management in areas designated as sensitive (such as nitrate vulnerable zones).

North America
Precision agriculture is most common in North America because the large farms and infrastructure are compatible with the initial concepts. In a 1998 survey (Akridge and Whipker, 1998) it was estimated that 75% of adopters were farming >200 ha and 15% >400 ha. The most common technology adopted was bio-engineered seed followed by field mapping (Table 1, based on use of services available for hire). In general adoption of services is higher were crop values are greater. In a 1996 survey it was estimated that 9% of corn farms used some sort of precision agriculture service and accounted for 20% of the cropping area.
Table 1: Growers use of precision agriculture services (based on random sample of agricultural dealerships (Akridge and Whipker, 1998)

<table>
<thead>
<tr>
<th>Growers use of:</th>
<th>% adoption (based on random dealer survey)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil sampling with GPS</td>
<td>8</td>
</tr>
<tr>
<td>Field mapping</td>
<td>29</td>
</tr>
<tr>
<td>Field mapping with GIS</td>
<td>6</td>
</tr>
<tr>
<td>Yield monitoring</td>
<td>14</td>
</tr>
<tr>
<td>Bio-engineered seed</td>
<td>52</td>
</tr>
<tr>
<td>VRT manual</td>
<td>18</td>
</tr>
<tr>
<td>VRT single controller</td>
<td>7</td>
</tr>
<tr>
<td>VRT multiple controllers</td>
<td>4</td>
</tr>
</tbody>
</table>

Oceania  Developments in Australia are well advanced with particular emphasis on cotton production and cereals. Adoption patterns are similar to other developed regions, but the generally larger land holdings make current technologies more attractive in this region.

4.2 ELEMENTS OF PRECISION AGRICULTURE

4.2.1 Crop selection

The selection of crops for precision farming is the same as that for conventional agriculture in a given region. It is assumed that the best crops are already known and that suitable varieties are selected (including bio-engineered options). In some instances different varieties might be planted in different parts of a field if there is sufficient evidence to support such an action.

4.2.2 Land preparation

The tillage of a field is likely to be little different from conventional practise. There has however been some development in variable tillage such as the optimisation of power harrow usage to create uniform quality seed beds and minimise soil damage (Scarlett et al., 1997). The timing of operations will be controlled by the same factors as for conventional management.

4.2.3 Sowing

Variable rate seeding is possible using modifications of existing precision planter designs. It is generally assumed that where the field is most fertile it is worth planting more seed however the scientific principle behind this assumption is not clear because other limiting factors may be influential. The findings of Bullock et al. (1999) indicate that economically, it is only worth using variable rate seeding if a good mechanistic understanding of the expected response is possible. Variable seeding is only worthwhile if other precision techniques are used to control the factors limiting germination and subsequent growth.

4.2.4 Management

There are two principal elements of precision management: variable rate fertilising and targeted agro-chemical application. In the former, the application of mineral fertiliser is controlled on the basis of spatial patterns found in the field and expected crop yield (Haahr et al., 1999; Peters et al., 1999; Welsh et al., 1999), and in the latter spraying is targeted based on infestation maps (Gerhards et al., 1999; Heisel et al., 1999; Schwarz et al., 1999). The timing of these operations and their efficiency will be controlled by the same factors as for conventional agriculture.
4.2.5 Harvest

Perhaps the most widely known element of precision agriculture is the concept of the yield map. This is a map of yield variation across a field produced during harvest (Figure 2). It is a measure of the performance of the system and also it is believed to be useful for determining what variable rate management is needed in the coming year. The spatial management of land based solely on yield makes little sense because there are many factors influencing the performance of the system. Initially yield maps can be used to identify chronic problems, or locations for detailed investigation, however by building up a yield picture through time (5-10 years) it is possible to establish the best performing parts of a field (Blackmore, 2000). One element of research that is seriously lacking is the role of field micro-climate in determining variation within a field, and the role of weather in modifying the limiting factors that control spatial variability of yield within a field.

4.2.6 Post-harvest considerations

Post harvest considerations in terms of crop handling and storage do not differ from conventional agricultural practice. In the planning phase of the precision agriculture cycle it is perhaps going to be necessary to have a complete weather picture for the farm so that yield map interpretations can be as thorough as possible.

4.3 AGRO-ENVIRONMENTAL INFLUENCES ON PRODUCTION BY PRECISION AGRICULTURE

4.3.1 Climatic requirements and limitations

In a review of the likely future weather/climate data requirements of agriculture, Seeley (1994) identified precision agriculture as a development that farmers would have to adopt in order to remain both profitable and sustainable. In the review it was concluded that improved forecasts and climate services would be required in conjunction with a programme of education to ensure potential users could get the most from future developments by National Meteorological Agencies. In a recent review of agrometeorological needs in Ireland, Murphy and Holden (2002) concluded that there was a need for “[Conclusion 6:] A national climatic atlas containing regional climatologies for all common and emerging agricultural enterprises suitable for sub-county scale regional planning...” in conjunction with “[Conclusion 1:] Forecast services should be continually improved with an emphasis on regulated, accurate, localised weather forecasts that can be tailored to specific user demands. Additional observation requirements should be added to the network to improve localisation and tailoring of forecasts”. Without specifically addressing the concept of precision agriculture, and by surveying farmers and other experts, it was concluded in this review of needs in Ireland, that localisation and tailoring of climate data and forecasts was required. Climate services for precision agriculture will definitely need to provide more localised information than is currently the norm.

Bullock and Bullock (2000) evaluated the value of agronomic data in the context of precision agriculture and concluded that it is now more valuable than ever. They also concluded however that site specific experiments (e.g. nutrient input trials at a given research station) are no longer sufficient, and that in order to understand how to vary inputs within a field, it is first necessary to understand fully how that field fits into a larger geographical context (e.g. how do recommendations for a dry continental climate compare with other similar climates, and with a warm maritime climate?). In other words, the question that needs to be answered for precision agriculture to be successfully applied is why input rates need to differ, and to isolate the larger geographical effects (e.g. climate) from the repeatable small scale effects (e.g. soil type) and the site-specific effects (e.g. nutrient status). This means that management decisions
must be understood in terms of regional agro-climatology. Power et al. (2000) reported results from the type of experiment called for by Bullock and Bullock (2000) – the Management Systems Evaluation Area project – which was based in 9 mid-western states (USA) for evaluating best practise nitrogen management. The project (as reported) found important results with respect to how things are done, but could offer little assistance with regard to accounting for weather effects. Perhaps because of the difficulty in running large (and long) enough experiments to account for weather. There are few authors willing to discuss the matter in anything other than aspirational or general terms.

Paz et al. (2000) evaluated the role of managing plant population and variety of soyabean within 50 x 50 m areas of a 20 ha field based on 34 years worth of weather data integrated in the CROPGRO-Soybean model. It was found that tuning the plant population in each grid to the current year’s weather gave a better yield than using either the 34 year average population of each grid or a 34 year derived uniform population (i.e. the same in each grid cell). However because the day-to-day variation in weather cannot be predicted far enough into the future, the best method theoretically is not the best method when weather risk is factored in. It was concluded that the best approach to variable rate population was to determine, with the model, the optimum population within each grid cell and to use that (i.e. to fine tune management units on the basis of climate). It was also found that varying the variety within the field offered no significant advantage. Use of a pest resistant variety (that maybe offered less yield under ideal conditions) over the whole field provided the best return. These finding suggests that there is a need to establish micro-scale (sub-field scale) agro-climatologies for specific crop types and related to soil type that can be nested within regional agro-climatologies on order to assess the long-term climate effect on within field variability.

Collis and Corbett (2000) suggest that, using geographic information systems, it should be possible to interpolate climate data to create “climate surfaces” which can be used as inputs to simulation models at locations where data are not available. This would allow regional scale planning of precise agricultural production. Further value could be derived from this approach by integrating the climate surfaces with historical weather data to undertake risk assessments related to variable rate inputs. The idea of using climate data to predict average risk and then using forecasts of seasonal weather is considered by Cook and Bramley (2000), but the value of seasonal forecasts is questionable so the method probably lacks utility. The concepts of “agroecozones” for the extrapolation of management data and agronomic research was reported by Anderson et al. (1998). A review of this approach would be worthwhile prior to developing regional agroclimatologies.

There are two climate specific issues that can be managed with precision agriculture. These are irrigation and pests/disease management. In the former case irrigation water is supplied based on available soil water and plant extraction demand (by creating irrigation management units), and in the latter case, spray and other intervention is applied non-uniformly depending on outbreak and magnitude of the problem. The case for variable rate irrigation is quite compelling – anywhere where climate will demand crop irrigation, in order to get the most from available irrigation water it will be necessary to match input to soil type, expected crop development and other known or expected limiting factors (for example, why irrigate a part of the field that will yield very little saleable crop?). In general terms, the nature of spatial patterns in the field will dictate how successful variable rate irrigation will be (Sadler et al., 2000). There is much scope for input requirement prediction using remote sensing tools (e.g. Barnes et al., 2000), but there is no guarantee of success (Feinerman and Voet, 2000).

Integrated pest management (IPM) was perhaps one of the earliest developments that can be thought of as belonging to the suite of tools now known as precision agriculture. Dent (1995) defines IPM as “a pest management system that in the socio-economic context of farming systems, the associated environment and the population dynamics of the pest species, utilises all suitable techniques in as compatible a manner as possible and maintains the pest population levels below those causing economic injury.” This can be paraphrased to: only do what is necessary, where it is necessary, to achieve the desired result. Cammell and Way
(1987) identified a number of climate factors that are central to IPM. The climate (in conjunction with specific species biology) will dictate the geographical extent of a particular problem, or may effect the geographical extent of predators used for natural control. The approach that precision agriculture takes to pest management will be dependent on location and local problems. The control methods advocated should be in tune with the local climate.

4.3.2 Meteorological requirements and limitations

The meteorological impact on precision agriculture is very significant. There has been much work looking at how to sub-divide fields for variable rate management but the assessment of such procedures tends to reveal that the best result could only be determined with hindsight and that the forthcoming season’s weather, which cannot be known, will be most important in dictating the best precision agriculture approach (e.g. Fraisse et al., 1999; Braum et al., 1998; Braga et al., 1998). The role of modelling has however allowed the concept of developing risk assessments prior to engaging in variable rate applications. Cook et al. (1996) concluded that seasonal weather variation was the most important source of uncertainty creating unacceptable risk when trying to implement variable rate application. Precision agriculture requires accurate, localised and tailored forecasts with time horizons from nowcasts, through 3- and 5-day forecasts to seasonal forecasts. A brief assessment will be made of the role of the principal meteorological elements and their interaction with precision agricultural practise.

Radiation

The role of radiation in precision farm management is not well investigated. This is perhaps because it is assumed to be effectively constant over quite large areas, or rapidly changing with moving cloud patterns. Runge and Hons (1998) concluded that even though it should be theoretically possible to adjust plant densities to maximise use of available radiation, there is insufficient effect (or forecasting) to make this worthwhile. Radiation is an input to most mechanistic and empirical models of crop growth (Barnett et al., 1997), but for practical purposes is assumed to be constant over the area of a field. Matthews and Blackmore (1997) used the CERES Wheat model to evaluate whether permanent influences on available solar radiation (topography and aspect) could be included in the development of a variable rate nitrogen application plan. They concluded that optimising nitrogen inputs would allow a 15% saving over uniform management if the topography of a field were accounted for in the pre-planning stage and inputs were balanced to the expected effect of reduced solar radiation. At a more basic level, McEntee (1976) concluded that south facing slopes up to 20° receive 137% more radiation in the spring and autumn (in Ireland) than a horizontal surface, and that a north facing slope receives only 76% of incoming radiation. Given this impact, plant density and nutrient management on a sub-field basis should perhaps be tailored to the typical available radiation in areas where canopy is unlikely to be light saturated. Furthermore, the impact of cloud on available radiation (as expressed by the Ångstrom formula, Keane, 2001) over periods of a week or month may have significant influence on the on-going management of a crop in the field. Climatic difference from year-to-year may be important given the interaction of cloud cover, aspect and slope. It can be concluded that there is a need to systematically evaluate the impact of solar radiation variation for each field on a farm that is being managed using precision techniques to ensure that variation in incoming radiation (climatic) can be accounted for in simulation models. The impact of year-to-year change in synoptic situation which will significantly effect the available radiation at critical growth periods in some parts of the world also needs to be assessed.

Precipitation

For many farmers, after planting a crop, the big questions are: When will it rain? Will it rain too much? Will there be drought? Will the temperature allow the crop to get the most from the available rainfall? (Runge and Hons, 1998). Uncertainty about rainfall is the biggest problem
for precision agriculture both in terms of planning a season-long management campaign and planning particular site-specific activities over a week-long time horizon.

Sadler et al (1996) established that for the south-east USA coastal plain, in a “normal weather” year, crop-water relationships were the most important factor dictating variation in yields (of maize, wheat and soyabean). Similarly, the pattern of yield of wheat in Australia is closely related to the water storage capacity of soil and its spatial variability (Moore and Tyndale-Biscoe, 1999) but where irrigation is used, the impact of yearly variation in weather is moderated.

O’Neal et al (2000) examined the magnitude of spatial variability in rainfall in eastern Indiana (USA) and found up to 1.73 mm/day variation in rainfall over the area of a farm. When the rainfall data over a four year period were compared by variation during phenological stage it was found that the magnitude of this temporal variability (up to 3.40 mm/day) was greater than the spatial variability. This was interpreted to mean that more attention should be paid to the importance of a network of on-farm rain gauges, and the sensitivity of crop models (used for precision management) to the precipitation input. Bosch and Davis (1998) studied rainfall patterns and distributions in Georgia (USA) and concluded that meteorological observations more than 2 km from the farm were of little use for simulation modelling. If this idea can be extended to other regions, this means that precision farmers will require on farm meteorological observations for data input to decision support systems that are integral to the precision production process.

Bakhsh et al. (2000) analysed multi-year yield maps from Iowa (USA) and have found a link between the seasonal rainfall total and small-scale variation in crop yield (having accounted for other factors). This raised the question of whether the precipitation effect, related to soil physical properties and water availability patterns, is of great significance. The Environmental Policy Integrated Climate (EPIC) model was used by Lu and Watkins (1997) and Watkins et al. (1998) to study the impact of variable rate nitrogen management on potato crops. Interestingly, they found that spatially variable water management may have a greater impact on yield than nitrogen management. Given that water management can be based on 4-5 day forecasts that are reasonably reliable, this is a very significant consideration. Matthews and Cosser (1997) used CERES Wheat to establish yield/nitrogen response curves for various parts of a field over a number of years. They found that the optimum application rate was closely related to weather in a particular year. In wet years there was little potential for reducing inputs, but in a dryer year up to 25% less fertiliser could be used.

It can be concluded that precipitation has two major impacts for precision farmers: the impact of available water – which can be managed by irrigation in some cases, and based on reasonably reliable 5-day forecasts; and season-long management planning that integrates a season-long strategy with short-term input management. There is a need to evaluate the density of rainfall observations on farms, and the integration of on-going data collection, 5-day forecasts and information on the deviation from climatic norms to create site-specific management planning strategies.

Temperature

Temperature is a primary factor influencing crop growth (Keane, 1986). The influence of temperature on yield however is moderated by both the available radiation and the available water, thus if either of these factors are limiting, a crop cannot develop to its full potential for a given thermal condition. In general the effect of temperature on crop growth is additive so rate of development can be related to thermal time (accumulated degree days, °C_days):

\[ °C_{\text{days}} = \left( \frac{T_{\text{max}} - T_{\text{min}}}{2} \right) - T_0 \]  

(Eqn. 1)
where \( T_{\text{max}} \) and \( T_{\text{min}} \) are the maximum and minimum air temperatures recorded at 09:00 and \( T_b \) is a crop specific base temperature below which growth does not occur (note: negative accumulation is ignored). This well known approach to thermal time is of relevance to precision agriculture largely because of its interaction with topography and slope. Just as with incoming radiation, the effect of slope and aspect is significant in a field. A south facing slope (7° -12°) will accumulate 3-7% more degree days compared to nearby level ground, and a north facing slope may accumulate 10-20% less (Keane, 1986). This has significant implications for frost, snow melt, germination, emergence, ripening and land access. All of these factors will combine to influence yield patterns in a field and dictate what limiting factors are manageable with available variable rate technology and decision support systems.

There are significant differences between ambient air temperature and the canopy temperature. Sadler et al. (2000a) evaluated the CERES Maize model as a precision agriculture tool. They found that it was quite sensitive to maximum air temperature effects and concluded that because crop temperature is more variable than air temperature, it would be useful to find a means of estimating variation in crop temperature to make the model more spatially variable. Further work by Sadler et al. (2000b) indicated that the difference between canopy and air temperature in Maize crops reflected drought stress (>10°C difference where stressed as opposed to <2°C where not) which means that the available soil water can be used to estimate canopy temperatures in certain conditions. It is however perhaps reasonable to avoid trying to estimate variation in canopy temperature if the available simulation models are not designed to work with it as an input variable because of the difficulty in obtaining suitable quality data.

Temperature also has a significant effect on the emergence of pest populations (Cammell and Way, 1987). Emergence of adult pests and egg hatch can be shown to be related to thermal time (e.g. Lewis and Sturgeon, 1978), but the degree to which this is site specific is not clear.

The accumulation of thermal time, compared to the climatic norm, is also of relevance to precision agriculture. Particularly so when thermal time accumulation varies across a field and other physical factors integrate with it to create the field yield response. Runge and Hons (1998) concluded that when temperatures were below average for a year, the inputs on poor yielding soils should be reduced as the plants will have little opportunity to utilise the resource. There is a need to investigate the use of deviation from climatic norm (based on observation and forecast) as an input to precision agriculture decision support systems.

**Humidity**

There appear to be no published works that discuss explicit influences of humidity with respect to precision agriculture. The most significant influence will be on the development of pest and diseases that like a humid atmosphere (such as potato blight). There are various systems in place that use humidity as a key for predicting when infestation problems might occur (Mercer et al, 2001) such as Smith Periods (Smith, 1956) which are defined as “…two consecutive 24 hour periods, starting at 9 a.m. GMT, 10 a.m. British Summer Time (BST), in which the minimum temperature does not fall below 10 °C and there are at least 11 hours of 90% or greater relative humidity (RH) on each day” (Mercer et al, 2001). The important question with respect to precision agriculture is whether there are realistic possibilities of using such information to manage a field in a spatially variable manner that would be in any way different from conventional spraying. The purpose of the Smith Period is to predict when conditions are conducive to Blight development, and therefore spraying is not in response to a known outbreak, but to prevent any outbreak. Such a protection strategy is not conducive to a site-specific spraying policy but requires blanket inputs.
Wind

The most important aspect of precision agriculture that is influenced by wind is spray management. Spray timing is known to be critical for chemical efficiency, and with variable rate application the timing effect is likely to be even more important. Specific spraying systems have been developed to allow variable rate spraying in conjunction with variable spray characteristics so as to reduce wind drift (Giles and Comino, 1990; Giles et al., 1999). The range of flow rates that are possible with acceptable droplet size distributions depends on the chemical being applied, the wind conditions at the time and the available technology (Giles et al., 1999; Miller and Combellack, 1997). This means a localised wind forecast is likely to be of great use to precision farmers while a general regional forecast may have some merit but will be less valuable.

Another area of concern where wind is relevant is the application of machine vision systems for feature detection in crop fields and sensor systems. Systems for weed detection that rely on texture and shape of visible features (i.e. rely on clearly defining outlines and structures within an image) will be influenced by wind if the crop is moving and the mount for the camera is moving. In this case it will be difficult to get a sharp, focused image. The alternative here is to use colour based methods that are less sensitive to such interference (Faki et al., 2000).

The role of wind in pest management is also important because it dictates the direction and extent of pest migration. Irregular occurrence of migratory pests can be forecast by wind direction at specific times (e.g. Rainey, 1979) which may be of relevance to an IPM system integrated with a whole-farm precision agriculture management system.

4.3.3 Land requirements and suitability

Terrain and slope

The effect of slope and aspect on crop yield is by a moderating effect on radiation, temperature and soil water status. The influence of terrain will probably be, via soil, on the availability of water to the crop throughout the growing season. Kravchenko and Bullock (2000) related multi-temporal yield data to soil properties (explaining 30 % of variability), and topographic features (explaining 20 % of variability). Combined, soil and terrain influence explained about 40 % of yield variation in a field. This means that significant variability in yield must be accounted for by weather/meteorological/climate effects, natural biological variability, pest and diseases and other unknown factors. Kravchenko et al. (2000) used a multifractal analysis to assess the impact of terrain slope on crop yield over a 5 year period and found that the effect of slope was weather dependent. In moderate to dry years the largest within field yield was found on low slopes (suggesting more durable water supply), but in wet years these sites had the lowest within field yields (suggesting radiation or temperature limitation). Likewise, Timlin et al. (1998) found that yield was related to the curvature of a slope, but that it interacted with weather such that dry years had greater yield at more concave locations. The significance of this finding is that it is not possible to make plans solely based on climate and topography because seasonal synoptic variation will effect the yield and therefore the suitability of management decisions. Roloff et al. (1998) concluded that the environmental impact of variable rate fertiliser application in a small catchment (using the EPIC model) was minimal and there was little cash benefit to the farmer. This raises the significant issue of whether the data input required for precision agriculture (particularly the meteorological elements) is well balanced by potential gains; does/will it cost too much to fully observe weather based on landscape variation? Khakural et al. (1996a) established that low yields of maize and soybean were associated with crest and backslope positions in a glaciated landscape (USA) which could be used as information, in conjunction with seasonal weather data to relate maize yield with a productivity score for spatial interpolation and prediction (Khakural et al., 1996b), and perhaps this approach is the way forward for using weather information in precision farming.
Bouma et al. (1999) believe that knowledge bases containing results of multiple management decisions should be compiled on the basis of soil series (the type of soil to which the result applies defined by The Soil Science Society of America (1997) as "...a conceptualised class of soil bodies...that have limits and ranges more restrictive than all higher taxa...a major vehicle to transfer soil information and research knowledge from one soil area to another") which is perhaps contradictory to the opinion of Bullock and Bullock (2000) who advocated sorting data on the basis of larger, significant geographical areas (i.e. on the basis of climate). This idea was supported by the notion of White et al. (1999), who suggest that there is a need for soil micronutrient maps for large areas so that the interaction effect with climate can be established, and which may then help explain some of the variability found in a field. The soil-based and climate-based approaches are in fact complimentary given that climate can be regarded as one of the primary soil forming factors and that any modern relational database system would allow data to be reported using either approach. It is concluded that the compilation of agronomic research data suitable for precision agriculture should be on the basis of both soil types and climate.

Moore and Tyndale-Biscoe (1999) conducted a modelling experiment using 29 years worth of weather data (from Australia) and the CERES Wheat model to establish the influence of soil type, weather and nitrogen application as either a variable or uniform application on yield. They concluded that variable rate application related to soil type was most beneficial when there is great differences, or contrast, between the soil types. If there is a continuum (analogous to the idea of low to medium to high) of soil types within a field, then variable rate management will not show a clear beneficial return. They also concluded that it was soil water holding capacity that was most significant with respect to yield variability. One problem that arose during their work, which was due to weather effects, was that when trying to target nitrogen inputs to soil type (as opposed to using an average uniform application), it could lead to decreased yields rather than a similar yield for less input.

The interaction of soil and precipitation is of great importance, the work of Bakhsh et al. (2000) suggests that small-scale changes in soil structure might have a detectable impact on crop yield. Maidl et al. (1999) found that low sand content soils were productivity limited by soil structure formation, and that available moisture capacity was of vital importance for cereal yield. They concluded that the mediating effect of soil on weather impact could not be overlooked, and that variable rate nitrogen application is only valid when matched to plant development. This means that a season-long strategy will be difficult to develop due to the unforeseeable future that is long-term weather. The weather/soil interaction is illustrated by Thomsen et al. (1997), who found that yields in a highly variable field reflected difference in soil water holding capacity in those years that were relatively dry, but in wet years there was little variation in yield. Van Alphen and Stoorvogel (2000) have assessed soil functional units created at the field level by clustering, interpolation and boundary detection and discovered that classifying soil based on hydraulic properties (such as dry year water stress as estimated by a simulation model) will yield management units that can be used functionally in the ongoing farm decision making process.

Water status

Soil water status will reflect both the soil and the precipitation at a given location. Voltz (1997) examined the importance of spatial variability in soil water status within fields and concluded that (i) current agricultural simulation models take insufficient account of small scale variability in soil morphology and root development, (ii) the quantification of hydraulic properties of soil at a suitable spatial scale is difficult at with current technology, (iii) the scale at which pollution impacts become visible (catchment) is not well linked theoretically with the field scale processes driving it, and (iv) hydrological modelling may be a suitbale linking tool between field and catchment scales.
The importance of soil structure was also highlighted by Cambardella et al. (1996) who found that this was the most significant factor dictating soil water relations with respect to crop yield. Lord et al. (1997) evaluated wheat yields in conjunction with a range of other soil properties and found that soil available water capacity was only really related to yield in drought years, and in other years, crop water was not a limiting factor. Thus there is a significant temporal variability in the yield limiting factor. This therefore means that the weather contribution to soil water management should include a component that provides early warming of a potential water limiting situation that can be balanced by other management decisions based on the year-to-date precipitation. The other major issue here is the fact that the importance of soil/precipitation interaction is dependent on regional climate. Where water stress periods can be expected (e.g. dry summer), the influence on yield will be more marked.

Soil water status becomes closely linked in water stress situations with irrigation and water management. Nijbroek et al. (2000) found that irrigation scheduling for soybean could be matched to weather conditions, but they found little value in worrying about spatial patterns in the field and concluded that a uniform management based on the majority condition in the field would lead to the best return. This is somewhat contradictory to work that has focused on variable rate irrigation as a viable means of optimising water consumption (Sadler et al., 2000).

Land suitability classification and specification

There is probably only one specific land suitability limitation for precision agriculture and that is the type of spatial variability (pattern). It has been noted by Moore and Tyndale-Biscoe (1999) that management planning using models will work best when there are few soil types that are distinctly different. A further technical limitation is the pattern of spatial variability. The field application of different inputs depends on the technical limitations of the available machinery (the variable rate technology). There will always be delays when switching from one application rate to another (sometimes referred to as the “control time”). The effect of control time can be seen in Figure 3 where there is a clear period (about 20 s) where application rate (lower dashed line) is not at the desired rate (the target set-point, lower solid line). In a field with two, evenly sized, contrasting areas (Figure 4a), at normal operating speeds for spreaders and sprayers, this would not be a major problem because most of the field area would be managed at the correct application rate. In a situation with smaller target areas (Figure 4b), more error would be introduced, particularly where targets are created with quite small dimensions (such as the bottom left of Figure 4b). In a case where there are many, small target areas (Figure 4c), it is quite likely that very little of the field area would receive the correct input. This means that there is a need to quantify spatial patterns found in a field, quantify the nature of the resulting management units and their patterns, and to only use management units that are meaningful and can be addressed with available mechanical technology. A generalised land suitability procedure should be able to address this issue.

4.3.4 Environmental extremes and risk

One of the most significant environmental risks for the farmer is extreme weather (flooding, hurricane, tornado, hail storm,…). The normal alerts and alarms for extreme weather that national meteorological agencies supply to populations apply to precision farming, but one of the inverse interactions is using precision technology to quantify the impact of extreme weather on the farmer. This is of significance for farmers who rely on insurance as a risk
management tool. Erickson et al. (1999) used remote sensing techniques to assess the extent of hail damaged areas (in Indiana, USA) which were similar to those used for precision farm management. Similarly the extent of flooding is clearly visible from satellite remote sensed imagery. There is a significant potential for using precision technology (yield maps, near-field and remote sensors), and simulation models to quantify losses to farmers due to extreme events.

4.4 DATA AND MODELS

4.4.1 Data availability and resolution

The availability of national meteorological data (i.e. data collected and quality controlled by a state (or similar) agency) suitable for site-specific management is probably poor in most countries. It is reasonable to say that the state agencies or meteorological services will never manage to create a sufficiently dense observation network for precision agriculture. Even numerical weather prediction is unlikely to provide sufficient resolution data for running models directly. There is a possibility of using localised interpolations to estimate variation in meteorological elements as suggested by Dozeman et al. (2001) within a NWP prediction grid cell (Figure 5), but this is perhaps of limited value.

The ideal resolution for meteorological observation is probably one site per farm (minimum), and if the land-holding is extensive, or covers a range of land types (e.g. different aspect, extremes of altitude), then a weather station for each land type should be considered. To achieve this density of observation it will be necessary for farmers to invest in automatic weather stations and to learn how to maintain and use them. The role of the national meteorological agencies then becomes provision of a means of quality control services (e.g. by using tests or comparisons such as with the regional 95% distribution or the synoptic situation). In exchange for such activity, it may be possible to use the national agencies to collate farm

Figure 4: A. Two clear management units of large size. B. Four management units or moderate size. C. Many small management units of small size

Figure 5: Schematic of one possible approach to estimating fine resolution weather data from NWP output
based observations to improve now-casts and other forecast tools, and to create a finer resolution archive of meteorological observations in farming areas. In terms of creating a knowledge base of weather from a wide range of geographical locations and soil types, this is the most practical approach. It is desirable that such a system be developed to help separate the weather and soil effects in each geographical region.

4.4.2 Specification of "ideal" data

It is very difficult to specify ideal data for precision agriculture because of the interaction of spatial and temporal effects (climate, meteorology, micro-climate, micro-meteorology, region, country, county, catchment, farm, field, sub-field, plant). Protz et al. (2000) indicated a minimum soil data requirement which includes "yield maps of major crops from each of a dry, wet and normal year from each crop in the rotation" (note that this refers to Ontario, Canada, for other regions the principle would be positive, normal and negative weather relative to climatic norms). A quick assessment of this minimum requirement indicates that for a 3 crop rotation, at least 9 years of yield mapping is required (assuming the weather is kind and gives the farmer what is needed) and probably much more. This indicates that to achieve the type of data that are needed to relate field performance to weather effects, it may be necessary to use localised and/or calibrated simulation models to reduce the time needed for developing a precision management approach. It is reasonable to say that the required accuracy and observation interval will be controlled by the performance of automatic weather stations (because this is the technology available to farmers), but this should not constitute a major problem with current (and future) technology. First draft specification of meteorological data requirements for precision agriculture are:

1. Air temperature
   (15 min interval, at least one observation per farm or land-type, ±1°C)
   - maximum,
   - minimum
   - derive average daily values
   - derive climatic data
   - derive extreme risk probabilities

2. Rainfall
   (per 0.5 mm rainfall or every 15 minutes, at least one observation per farm or land-type, ± 1 mm)
   - continuous
   - derive average daily, monthly values
   - derive climatic data
   - derive extreme risk probabilities

3. Wind
   (15 minute interval, at least one observation per farm or land-type, ± 0.5 m s⁻¹)
   - speed
   - direction
   - derive run of wind
   - derive climatic data
   - derive extreme risk probabilities

4. Solar radiation – 60 minute interval
   (regional with local estimation of deviation due to topography and shading, ±10%)

5. Soil temperature – 60 minute interval
   (regional with local estimation of deviation due to topography and shading, ±10%)
   - maximum,
   - minimum
   - derive average daily value
- derive climatic data
- derive extreme risk probabilities

6. Relative humidity
   (15 minute interval, at least one observation per farm or land-type, ±1%)
   - derive average daily values
   - derive climatic data

7. Evapo(transpiration)ation (potential)
   (60 minute interval, at least one observation per farm or land-type)
   - derive average daily values
   - derive climatic data

4.4.3 Agricultural production models

It is the opinion of Bouma et al. (1999) that one of the best uses of weather data are for backward looking evaluations of management decisions using simulation models. The idea is to evaluate all management decisions and to isolate the best and worst aspects of management (with the benefit of hindsight) and to learn from the result, so that over a period of time, a solid body of knowledge about the management at a given location can be developed. For this to be possible, a range of suitable mechanistic production models, localised, tested and calibrated for various world regions will be required. An obvious starting point for such an approach is the DSSAT model system (Tsuji et al., 1994) which incorporates both CROPSGRO and CERES models (Figure 6). In a similar vein to the work of Moore and Tyndale-Biscoe (1999), Paz et al. (1998) used CERES Maize to evaluate the economic benefit of variable rate application using 22 years worth of historical weather data. While they found that the model could be made to work well, they provided no assessment of how the model could be used for forward planning. Braga et al. (1998) also managed to make the CERES model work well, but found between year weather variability was a large, unpredictable influence on yield and thus confounded the development of a reliable nitrogen management strategy. Using the Integrated Crop Ecosystem Management Model (ICEMM), Boone and Landivar (1998) were able to predict field cotton yields but had difficulty predicting sub-field yield accurately which they ascribed to problems with defining soil variability within the model. Thornton and Wilkens (1998) are of the opinion that the best use of simulation models with current knowledge is to simply quantify the risk associated with moving to variable rate input management.

4.4.4 Knowledge gaps

A perusal of early literature suggests that there was an assumption underlying precision agriculture that spatially variable soil/crop interactions would be consistent over time. It has now emerged that seasonal weather effects cause significant difference in yield from year-to-year at a given location (Sylvester-Bradley et al., 1999). Work like that of Kravchenko et al. (2000) and Timlin et al. (1998) has started to explain some of the climate, weather and terrain interactions that can dominate the soil effect, and the ideas of Moore and Tyndale-Biscoe (1999) regarding the magnitude of soil effects add to the knowledge base. It is still clear however that there is a huge knowledge gap when it comes to fully understanding even the limit of what can be done without a season long forecast. It is essential that the soil/weather interaction for major geographical regions be fully understood with respect to the local
agriculture system, and this knowledge is cast in the framework of precision agriculture technology.

### 4.4.5 Available decision making and knowledge management tools

There are many decision support tools and models available for research and production. It is not possible to examine each here, but an illustrative range of examples are presented to indicate what is possible, and to suggest what still needs to be developed.

An illustration of the type of management tool required for precision agriculture is that suggested by Ward and Holden (1998). They presented a conceptual system for precision peat production in Ireland. The system applies the concepts of precision agriculture to the peat energy business (particularly important in Ireland and Finland) where the “harvest” of peat is dependent on the season's weather, particularly the occurrence of 4 day dry spells in the summer months. For peat production the most important factor is drying which is dependent on peat type and weather. The peat type can easily be mapped by remote sensing (McGovern et al., 1999) and there are models of peat drying. The necessary step for the peat industry is to integrate the output of numerical weather prediction models with the drying models to produce site-specific milling application maps.

Audsley et al. (1997) described a planned decision support system for arable crop production which is using, as a first step, a fungal disease model that is weather driven so that users can ask “what if?” questions to assess whether the use of a variable rate plant protection approach would be too risky. To successfully create a useful support tool, this system will have to integrate crop biology, fungal biology, biochemical responses to plant protection chemicals, and disease spread models.

Management-Oriented Modelling (MOM) was presented by MengBo et al. (1998) as a means of integrating season-long management with short-term weather forecasts to try and establish the best option for an environmental benefit from precision agriculture while still having acceptable risk. This type of system looks at deviations from long-term averages to quantify how the season’s production is going, and how it might be improved. The long-term potential of the system is not yet clear, and as is emphasised by Harris (1997), benefits will only accrue if there are constant results in the face of variable weather.

COMAX is an expert system for cotton management that has been integrated with GOSSYM cotton model (Baker et al., 1983) to produce ICEMM which allows decision support for cotton management (Boone et al., 1996). ICEMM simulates the biological and physical processes of cotton development and yield over a range of soil types and climates. In addition it integrates farmer knowledge and cultural practices (planting density, row spacing, variety, pre-plant fertiliser applications, date of crop emergence, in-season fertiliser, irrigation and plant growth regulators applications), soil physical characteristics (bulk density, hydraulic properties and initial fertility and moisture status), and daily weather data (maximum and minimum temperature, total solar radiation, rainfall and wind) to provide a report of predicted plant height, number of fruiting nodes and vegetative nodes, number of squares, green bolls, open bolls and abscised fruits, carbohydrate, nitrogen and water stress on a daily basis. A summary table at the end of a full-season run presents the date of maturity, plant height, LAI, yield and the number of nodes, squares, green bolls and open bolls at each designated developmental event.

The DSSAT model system provides similar tools for most arable crops, and has been tested in most regions of the world (e.g. Uehara (1989) in the tropics, Bowen and Papajorgi (1992) in Albania, and Luo et al. (1998) in Asia – there are many more examples available).
4.5 INTERACTION WITH THE AGRICULTURAL COMMUNITY

Precision agriculture is by definition a high-tech, advanced approach to agriculture (e.g. the inclusion of “information technology” and the implication of various other technologies such as GPS, remote sensing, sensors, yield monitors, computers, models, software). This does not mean that it has to actually be high-tech, but that is the implication. The results of the technology mantle is that dissemination of precision agriculture ideas has tended to be via the Internet, via machinery manufacturer’s brochures or by simplified articles in farming literature. This has resulted in farmers in some parts of the world not properly understanding what it is all about. In 2002, in Ireland for instance, there are few agricultural advisors who are familiar with the ideas and who can present a balanced view of what precision agriculture can offer to the farmer. In less developed parts of the world, its value is probably even less clear. Until the theory stabilises and can offer farmers a system that has predictable and manageable risk, it is unlikely that there will be a large scale dissemination programme to publicise what the technology can offer – it is more likely that the separate elements will be adopted on an ad hoc basis depending on local manufacturers and suppliers to publicise and push specific pieces of equipment or technologies.

Dissemination of information to farmers is currently very limited. The research community has a number of regular scientific conferences (European Conference on Precision Agriculture – Warwick (UK), Odense (Denmark) and Montpellier (France); Precision Agriculture International Conference – held in the USA, now in its 6th year; specialist sessions at the American Society of Agricultural Engineers International Meetings, and others…), and in more developed countries there are various extension programmes. Most manufacturers, and many research centres have Internet web sites promoting their equipment and work. These are of course, only accessible to the technophile farmers. The vast majority of farmers in the world today have no access to such information sources. Experience of attending trade shows in Ireland suggests that distributors are not pushing precision agriculture technology, or information about it, to farmers in a big way. This has fallen more to the farming press.

A typical precision agriculture end users is a technophile farmer willing to experiment with new innovations. An example is N. Langkilde of Bramstrup, Denmark who presented his experiences at a research conference in Europe (Langkilde, 1999). He concluded that the main impact of precision agriculture has been to change farmer perception of what is actually possible. The most important impact has in fact been to require a work force capable of independent, self-management who are well educated. It is worth noting here that Langkilde observed that in 1999, a single field on his farm consisted of 22 separate fields in 1775, 5 in 1875, and had become a single field in 1975. He now believes that technology is available to treat that single field area as 200 (or even 2000) separate units. This is perhaps an overly optimistic view! This, it must be remembered is the view of an “early adopter”. If the typical technology adoption curve (Figure 7) is examined we can put Langkilde in the first 2.5% of “innovators”. The innovators are a group of farmers who will try anything that looks good, and will work to try and make technology really happen for the people who come after them. Based on the data in Table 1, the US is in the area of “early adopters”, as is Europe to some extent. Most developed countries are perhaps in the boundary region between innovators and early adopters. Globally, farmers are in the innovator phase. Those farmers in the early adopter category will reap the benefit of the technology before anyone else. They also bear the growing pains associated with it because it is new and unproved technology. The time spent learning how to use the technology and incorporating it into their production systems makes the total cost of ownership high. It is perhaps not unreasonable to suggest that precision agriculture
is now approaching the “chasm” stage in the developed countries. Its early promise is not coming good, and farmers are waiting to see if it can really be made to work. Part of the problem here is the perception that precision agriculture is for the large, wealthy farmer, but the lack of sound theory and data (as evidenced by the lack of impact of agro-meteorology on precision agriculture research) is also responsible for the chasm. Assuming that technologies such as DGPS directed bulk spreading, georeferenced soil sampling and decision support systems become commonplace, a much larger group of farmers will use precision agriculture technologies. These farmers will be the mainstream adopters, comprised of the early majority and the late majority. They will reap the benefits of the technology with far less troubles then their predecessors, but often lose the advantage associated with being on the leading edge. Lastly, there are always a few farmers who are very slow to take advantage of new and emerging technologies. These farmers wait until the technologies are very mature before integration with their day-to-day activities.

Potential gains of using agro-meteorological data need to be emphasised to the agricultural community because of its worth for both decision making and risk management. From the precision agriculture perspective, the value of agro-meteorological data has not been fully explored, but it is not inconceivable that the data itself, translated into hard information, may become a valuable asset of the suite of tools that comprise precision agriculture.

4.6. SUMMARY OF FINDINGS

term of reference a)

To define properly the mentioned fields of agricultural production:

• “the use of information and information technology to make and implement management decisions at the appropriate scale” (Holden, 1999)
• “…a management strategy that uses information technology to bring data from multiple sources to bear on decisions associated with crop production.” (NRC, 1997)
• “…carefully tailoring soil and crop management to fit the different conditions found in each field” (Chris Johannsen, Purdue University)
• The term “precision agriculture” means an integrated information and production based farming system that is designed to increase long-term, site-specific, and whole farm production efficiencies, productivity, and profitability while minimising unintended impacts on wildlife and the environment by: (a) combining agricultural sciences, agricultural inputs and practices, agronomic production databases, and precision agriculture technologies to efficiently manage agronomic and livestock production systems; (b) gathering on-farm information pertaining to the variation and interaction of site-specific spatial and temporal factors affecting crop and livestock production; (c) integrating such information with appropriate data derived from field scouting, remote sensing, and other precision agriculture technologies in a timely manner in order to facilitate on-farm decision making; and (d) using such information to prescribe and deliver site-specific application of agricultural inputs and management practices in agricultural production systems (www.spatialtech.org/pabill.html)

term of reference b)

To determine the most important agrometeorological and agroclimatological aspects of the mentioned fields of agricultural production:

• Climate services for precision agriculture will need to provide more localised information than is currently the case so that management decisions can be understood in terms of regional agro-climatology
• Precision agriculture requires accurate, localised and tailored forecasts with time horizons from now-casts, through 3- and 5-day forecasts to seasonal forecasts
• Solar radiation variation (as effected by slope and aspect) needs to be systematically evaluated for each field to quantify its impact on crop yield
• Temperature variation (as effected by slope and aspect) needs to be systematically evaluated for each field to quantify its impact on crop yield.
• Rainfall uncertainty is a significant problem for precision agriculture both in terms of planning a season-long management campaign and planning particular site-specific activities over a week-long time horizon.
• There is a need to evaluate the density of rainfall observations on farms.
• The interaction of soil and precipitation is of great importance (as it influences water status).
• Wind will influence spraying management.

term of reference c)

To determine the most important management aspects in the mentioned fields of agricultural production that have agrometeorological and/or agroclimatological components:

• Forward planning – choosing a variable rate input management strategy that has acceptable risk levels
• Yield map interpretation – understanding why yield varied in a field. The role of radiation, temperature, precipitation and soil water status has not been closely related to micro-meteorology and micro-climate
• Weed management – patch spraying and variable rate/chemical spraying will be influenced by wind, precipitation and temperature
• Pest and disease management – spread and control will be weather influenced
• Irrigation scheduling and variable rate application – controlled by precipitation (and soil)
• Simulation models for precision agriculture management require weather data

term of reference d)

To review conditions and measures to optimise agricultural production in the mentioned fields where agrometeorology can play an important role:

• Risk modelling/prediction
• Crop production modelling
• Pest/disease/weed management
• Time management support

References


