Project Title:	Scoping study on air movement and CO_2 use efficiency in protected crops
Project Number:	PC 226
Project Leader:	C W Plackett, FEC Services Ltd
Report:	Final, July 2005
Previous Reports:	None
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Location of Project:	FEC Services Ltd
Project Co-ordinator:	
Date Project Commenced:	1st September 2004
Date Project Completed:	30th June 2005
Key Words:	Air movement, carbon dioxide, humidity, botrytis, fans

1 Headline

This report details the findings of a study into the state of knowledge of techniques relating to optimised air movement and CO_2 use efficiency in the UK protected cropping sector. Recommendations are provided to the HDC & its PC Panel relating to:

- How current knowledge on air movement / CO_2 use efficiency can be effectively communicated to the UK industry (across all key sectors of protected cropping) in order that better technology transfer can be achieved.
- What is the industry's need relating to additional and new knowledge that will benefit the UK PC sector and improve business profitability?
- How to advance knowledge on the subject at both a scientific and commercial uptake level.

The key conclusion from the study is that the general level of knowledge of good practice in air movement and CO_2 use efficiency is poor. However there is a wealth of knowledge available (some of which has been generated by previously commissioned HDC studies) that, if effectively communicated to the sector, can have immediate benefit to growers in the UK. In addition some further areas of work have been identified that will cost-effectively advance the effective use of air movement by UK protected crop growers in the medium and longer term.

2 Key Findings

The key findings from this study are:

- The general level of knowledge on air movement technology in the UK protected cropping sector is low.
- There is some excellent information available in the public domain (some of it in the form of HDC reports) that can be immediately applied by the UK protected cropping sector.
- Some effective technology transfer could significantly improve the uptake of effective air movement technology in the UK. This could take the form of a grower guide supplemented by grower training events.
- The concept of CO_2 use efficiency is not well understood by many growers. Again the effective communication of previously completed R&D could significantly improve this situation.
- Many of the concepts associated with air movement and CO_2 use efficiency are not crop/sub sector specific. On that basis much of the work can be carried out in a generic protected crops way.
- Some further R&D will help growers apply new techniques in a cost effective and profitable nature in the future. This particularly relates to the use of lower energy input systems such as the sealed greenhouse concept.

3 Background & Introduction

Recent spiralling fuel price increases and the requirements of meeting environmental targets for reduced greenhouse gas emissions are leading growers to question all aspects of energy use and greenhouse environmental control. One related area that is receiving considerable interest is air movement technology.

Horticultural technologists and a number of leading growers have identified that air movement techniques are largely undeveloped and misunderstood in the UK protected cropping sector. To that end they are now asking questions on how knowledge in this area can be made available to UK growers.

4 Research Method

The following methods have been used to carry out the work detailed in this report

1. Discussion and interview with:
   a) Key researchers who have previously worked on airflow related areas of work
   b) Growers who have experience (both good and bad) with the practical application of air movement technologies.
   c) Research workers who are currently working (or have proposed working) on air movement/CO_2 related topics.
2. Reviewing the physiological, agronomic and pathological requirements of crops & diseases and assessing the likely impacts of air movement.
3. Studying key items of literature (including scientific reference material).
4. Examining the dynamics of air movement in the greenhouse and applying simple physical principles to the methods that might be used.

5 Discussion – Objectives v Findings

5.1 Establish the current knowledge base of the UK horticultural industry with regard to air movement requirements for protected cropping and related technologies.

Our impression is that the UK horticultural industry is not very well informed about the requirements for air movement in greenhouses or about the potential benefits and disadvantages of encouraging greater air movement. Furthermore, growers do not even seem to be very familiar with the work on these topics commissioned by the HDC.

5.1.1 Published Information Available to Growers

The Final Report of PC47 concluded that persistent air movement requires air flow rates of at least 0.2 ms^{-1} but less than 0.5 ms^{-1} otherwise the movement induced in leaves begins to adversely affect plant growth and development (Bailey, Harral & Fernandez, 1994). Despite the qualification about the effect of higher rates of airflow, the report also concluded that air movement in excess of 1 ms^{-1} increased plant transpiration with the additional benefit of reducing fungal disease. However, making air move incurs an energy cost for the operation of fans. In addition there is an indirect energy cost due to the increased loss of energy through the glasshouse roof and walls associated with increased air movement.

Similar conclusions about the effects of air movement were reached by Bakker et al. (1995). They reported that work in the USA suggested an air speed of 0.5 to 0.7 ms^{-1} was optimal for plant growth with growth inhibition above 1 ms^{-1} and damage to leaves above 4.5 ms^{-1}. Indeed, the American Society of Agricultural Engineers (ASAE) recommends an air speed of less than 1 ms^{-1}. Bakker et al (1995) comment, that a ventilation capacity of 120 $m^3m^{-2}h^{-1}$ is required to maintain the desired environmental conditions in a closed greenhouse.

Bailey et al., (1994) made their measurements both in the presence and in the absence of a tomato crop. The uniformity of the greenhouse environment in the absence of the crop was greatly improved by air movement but even in the presence of the crop, the variation in the environment was reduced by induced air movement. As the tomato crop grew in height, so there was a decline in the uniformity of air speed induced by the fans. Once the crop was at its maximum height, a very high air speed was induced in the space between the top of the crop and the glasshouse roof while the fan had very little impact at the base of the crop. These measurements were not made within the crop canopy but were made close to the edge of the canopy (Fernandez and Bailey (1994). It is not known whether there are simple relationships between the air speed measured at the edge of the canopy and air movement within the canopy but it seems likely that the relationship will vary according to the architecture of the crop canopy. Furthermore, it is unlikely that atmospheric humidity within the canopy will be strongly influenced unless air movement penetrates the canopy. With modern technology, it is now more feasible to measure CO_2 concentrations and humidity actually within crop canopies and it would clearly be desirable to do this within the canopies of glasshouse crops both in the presence and the absence of induced air movement.

Reports relating to the degree of uniformity of greenhouse environments reach variable conclusions. Bakker and van Holstein (1989) collected data from numerous commercial greenhouses in Holland and concluded that there was a considerable lack of uniformity in many greenhouses. The lack of uniformity was usually associated with variable rates of air leakage, variable rates of heat loss and uneven heat emission in different regions of the greenhouse. Those authors did not measure CO_2 concentrations but Bakker et al. (1995) cited examples where both vertical and horizontal gradients of CO_2 concentration were recorded and in at least one case, were associated with differences in tomato production.

Cockshull & Horridge (unpublished) measured considerable vertical gradients in CO_2 concentration within Chrysanthemum crops growing at Donaldsons Nursery, West Sussex, with the lowest concentrations being recorded in the vicinity of the uppermost leaves while the concentrations above the crop and at the base of the canopy were higher. Interestingly, these 'low spots' disappeared once the flowers opened and shaded the upper leaves, presumably because the photosynthetic activity of the upper leaves was then reduced by the shading.

Langton and Hamer (2003a, b) found that the air temperature within a closed Petunia crop canopy was markedly lower than that in the bulk of the air above the crop on high-irradiance days, but not at night, whilst the humidity of the air within the canopy was routinely higher than that of the air above the canopy during both the day and the night.

There are also considerable gradients of temperature under thermal screens (Grange & Hurd, 1983) where it is to be expected that there will normally be relatively little air movement. However, we have not found any reports concerning the likely benefits of inducing air movement under such screens.

The Annual and Final Reports from PC 162, in which a computational fluid dynamics (CFD) model was used, demonstrated that there would be areas of reversed air flow and a 'dead' zone in conventional glasshouses (Davies, 1999, 2001, 2002). This work was done using natural air flow and, although the effect of the crop is not discussed in these reports, it does apparently form part of the submitted thesis (Reichrath, 2002). The model showed that these characteristics would be affected by external wind-speed and direction and that these effects would be associated with variation in the CO_2 concentration within the greenhouse. Fernandez & Bailey (1994) showed that in relatively still air on sunny days, spatial variations of up to 150 vpm CO_2 and 7°C were detected in a four-span Venlo, tomato greenhouse and that these were reduced to 20 vpm CO_2 and 1.6°C when fans were used. In contrast to the above reports, Adams et al., (2000) recorded that they observed little variability in environmental variables across two relatively modern commercial glasshouses.

The Report of PC47 concluded that air circulation could give substantial improvements in uniformity of conditions in the greenhouse. This uniformity was likely to be of significant benefit to growers seeking to eliminate problems with condensation and related problems which were made worse by spatial variations in environment. Air movement would also be of significant benefit in ensuring that inputs such as additional CO_2 are available to the whole crop and at the same concentration. The evaluation of air flow engineering options and of different approaches to analysing flow using models provided the essential basis for designing effective air movement systems for commercial greenhouses (Bailey, Harral & Fernandez, 1994).

The Report also commented that the introduction of fans would create some non-uniform air movement as the air leaving the fans would be moving faster than that approaching them. Greater uniformity was obtained by using perforated air ducts at floor level as the air is then discharged vertically and does not increase horizontal variations. The openings should be small so that the air emerges as a high-speed jet. This approach might usefully be combined with a CO_2 distribution system and it clearly has relevance in 'closed' greenhouse systems. It also has relevance to systems using micro-turbines as co-generators of heat and power for in some designs of the latter, the exhaust gases are passed continually into the greenhouse while the micro-turbines are working. Vertical air flow would also fit conveniently with 'hanging gutter' systems of production for tomato where there is a considerable space between the glasshouse floor and the hanging gutter carrying the Rockwood slab and the rooted crop. High wire systems for cucumber and pepper and even bed systems for the production of cut flowers such as chrysanthemum might even be adapted to use this system of air distribution.

5.2 Establish the current knowledge base with regard to optimisation of CO_2 utilisation within the greenhouse envelope. This is to focus on how CO_2 use efficiency might be improved and to determine the likely inter-relationships between air movement and CO_2 uptake efficiency.

5.2.1 Current Knowledge Base of CO_2 Utilisation

The actual knowledge of individual growers is highly variable but most are aware that plants grow by creating new carbon compounds from carbon dioxide (CO_2) and water (H_2O) when in the light and that the air surrounding the plants is the source of the CO_2. Growers also appreciate that the energy to create the new carbon compounds comes from sunlight; that the whole process of trapping this energy and creating new carbon compounds is termed 'photosynthesis'; that the green pigment, chlorophyll, in the cells of green leaves is responsible for capturing the energy of sunlight, and that as more light falls on leaves and is absorbed by chlorophyll, so the rate of photosynthesis proceeds more rapidly.

Most growers are also aware that the rate of photosynthesis proceeds more rapidly if the concentration of CO_2 around the leaf is increased (Hand, 1984). The typical response (Fig 1) shows that the amount by which the rate of photosynthesis increases gets less with each successive increment of 100 vpm CO_2 (Nederhoff, 1994). This diminishing response occurs over the range from 100 vpm to 1200 vpm CO_2 or so, above which further increases in CO_2 concentration have little beneficial effect.

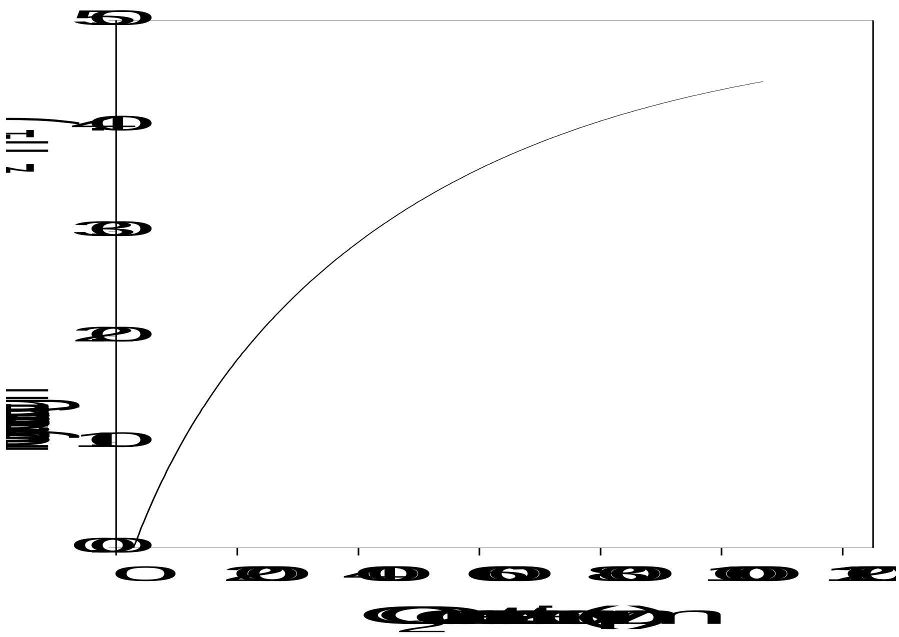

Fig. 1. Effect of CO_2 concentration on canopy photosynthesis of cucumber (after Nederhoff & Vegter, 1994)

The average concentration of CO_2 in the atmosphere outside the greenhouse is currently reaching 380 vpm or more but the average concentration within the greenhouse can be both higher and lower than this. Because of the pronounced increase in the rate of photosynthesis in response to increased CO_2 concentrations, and because this normally translates into increased yield or quality of marketable product for greenhouse crops, many growers deliberately add CO_2 to the greenhouse atmosphere (Hand, 1984). Pure CO_2 can be obtained from containers of the compressed gas but today, CO_2 for greenhouse cultivation is more usually obtained from the combustion of a hydrocarbon fuel in either a boiler or an engine. The exhaust gases may then have to be cooled prior to injection into the greenhouse atmosphere. The process of combustion may also generate gaseous pollutants and, if these are likely to prove harmful to the crop or to the workers, they must be removed before the CO_2-rich mixture of gases is injected into the greenhouse.

If the greenhouse ventilators are closed during the day, the photosynthetic activity of the crop can quickly lower the concentration of CO_2 in the greenhouse air to below that of the external ambient air, i.e. depletion of CO_2 occurs. Indeed, depletion can also occur in summer when the ventilators are open, presumably because the rate at which CO_2 in fresh air is delivered to the crop is exceeded by the rate at which CO_2 is removed in photosynthesis under these high light conditions. On the other hand, if the crop is now placed in the dark so that there is no photosynthetic activity, the concentration of CO_2 increases in the air around the crop, especially if the vents are closed. Indeed, it may continue to increase if the effective volume of air surrounding the plants is reduced, as occurs when a chrysanthemum crop is covered by a black-out screen (Cockshull & Fuller, 2001). In the absence of photosynthesis, CO_2 accumulates because it is produced by the respiration both of the crop and of micro-organisms in the soil within the greenhouse. As soon as the crop is exposed to light again, the CO_2 concentration falls as photosynthetic activity begins once more. In the case of the chrysanthemum crop, the removal of the black-out screen after dawn may enable the CO_2 concentration to fall very rapidly as that also allows air from above the screen to displace the CO_2-enriched air below it.

5.2.2 The Optimisation of CO2 Utilisation

Research and development on the optimisation of CO_2 utilisation has considered how this might be achieved with greenhouse tomato crops using either pure CO_2 or CO_2 derived from the exhaust flue gases of natural gas fired boilers (Chalabi et al., 2002a, b). The algebraic function that was derived from this work has not yet been incorporated into the programs of greenhouse environment control computers since many growers were reluctant to trust a computer program to supply CO_2 in a cost-effective manner under all conditions. Consequently, sets of simple guidelines were produced for growers together with two simple computer programs entitled "CO_2 Optimiser™" that could be run on a free-standing PC (Bailey, 2002).

5.2.3 Air Movement Requirements for Protected Cropping

5.2.3.1 The Movement of Carbon Dioxide

In order to reach the sites of photosynthesis within the leaf, the CO_2 in the greenhouse atmosphere has first to diffuse or be moved by wind to the immediate vicinity of the leaves. The gas then has to pass across the "boundary layer", a layer of still air that surrounds the leaf and forms the interface between the greenhouse air and the leaf surface. It is generally accepted that the boundary layer around the leaves of a crop is relatively thick when there is little air movement in the crop canopy and that it becomes thinner as the speed of air movement over the leaf surface increases, the more so if there is turbulence in the air passing over the leaf. By contrast, the presence of hairs on the surfaces of leaves may increase the effective thickness of the boundary layer.

Once across the boundary layer CO_2 passes into the leaf through the small pores (stomata) on the upper and especially the lower surfaces of leaves. These pores are usually open by day but close at night and they are the main avenue for gas exchange between the greenhouse atmosphere and the internal atmosphere of the leaf. The pores in the leaves cannot discriminate between different gases and so they are not only the main avenue by which CO_2 enters the leaf, they are also the main avenue by which pollutant gases enter and by which water vapour leaves the leaf. Finally, CO_2 must pass from the air spaces immediately below the stomata, across cell walls and into the cells of the leaf where the process of carbon fixation occurs.

The physical process that brings CO_2 from the boundary layer to the internal surfaces of the leaf is diffusion and the direction of movement is determined by the concentration gradient. As a result of photosynthetic activity in the cells of the leaf, the concentration of CO_2 in the internal air spaces within the leaf is usually lower than that in the greenhouse atmosphere and so the concentration gradient is from the greenhouse air to the internal air spaces. The rate at which CO_2 passes into a leaf is determined both by the steepness of the concentration gradient and by the distance that molecules of the gas have to diffuse across the boundary layer and through the stomata to the atmosphere within the leaf.

The air within the leaf is saturated with water vapour. The air in the greenhouse is normally not as humid and so the gradient for water vapour is the opposite to that for CO_2.

5.2.3.2 Air Movement and CO_2-use Efficiency

There is growing public awareness and concern about the release of CO_2 into the global atmosphere. Although the amount of CO_2 released by protected cropping is small by comparison with that from other sectors of commerce and road and air traffic, it can appear wanton for an industry to be generating CO_2 for the laudable goal of increasing crop yields but then allowing most of that CO_2 to escape into the global atmosphere through the open ventilators of greenhouses in summer.

In addition there are also sound economic reasons for using CO_2 more efficiently in greenhouse crop production. Obviously if crops can make better use of any available/delivered CO_2 then yield should increase and the resultant financial margins/profitability improve accordingly.

Hand (1984) defined CO_2 utilisation efficiency as "the net CO_2 uptake by the crop expressed as a percentage of the CO_2 that is added to the greenhouse atmosphere". In horticultural terms, it might also be defined as the weight or number of marketable products produced per unit of CO_2 added to the greenhouse atmosphere.

There seems general agreement that moving air within a greenhouse is beneficial as it creates more uniform aerial environments in which the CO_2 concentration in the crop canopy is more likely to be similar to that measured in the bulk of the greenhouse atmosphere (Bailey, Harral & Fernandez, 1994). There is much less agreement about the benefits of air movement on CO_2 uptake. Part of the uncertainty relates to the problem that the bulk of the theoretical work has dealt with plants in the open field while experimental work has concentrated on the responses of single leaves enclosed in small chambers. Consequently, there is uncertainty to what degree work on single leaves can be extrapolated to the leaf canopy (Jarvis & McNaughton, 1986) and the extent to which the enclosed or semi-enclosed environment of the greenhouse differs from that in the open field. These concerns are of considerable importance in horticultural crops such as tomato and chrysanthemum where the system of cultivation produces a dense canopy of leaves arranged as a hedge (tomato) or bed (chrysanthemum) and where there is evidence that the environment within the canopy is more humid and has a lower CO_2 concentration than the bulk of the greenhouse atmosphere.

If we accept that air movement is beneficial in bringing CO_2 to the leaf canopy of a glasshouse crop, the next barrier to the uptake of CO_2 is the boundary layer of relatively still air that surrounds the surface of each leaf. The theoretical aspects of leaf boundary layers are dealt with very competently by Jones (1983) and by Schuepp (1993). These authors conclude that the thickness of the leaf boundary layer has a marked effect on the rate of diffusion and that air movement will reduce the effective thickness of the boundary layer. This view has been supported by the calculations of many others (e.g. Bakker et al., 1995). However, Stanghellini (1987) concluded that air movement would have little effect on water loss from leaves, although her range of airspeeds from 0 to 0.5 ms^{-1} was relatively narrow. Schuepp (1993) concluded that the boundary layer thickness of a small leaf might drop from 2.8 mm to 0.28mm as airspeed increased from 0.1 to 10 ms^{-1}. The range of airspeeds used in the above example is very wide but values for intermediate airspeeds could be estimated from the expressions presented by Schuepp (1993). Others have calculated values ranging from 5 to 10mm for the thickness of the boundary layer of medium-sized crop leaves in relatively still air. Because of the difficulty of determining boundary layer thickness, Jones (1983) has suggested that it is more convenient to use boundary layer conductance and describes relationships for its estimation. Finally, Schuepp (1993) concluded that the leaf boundary layer thickness was increased by the presence of hairs on the leaf surfaces and by increasing leaf size. Hence, it would seem that cucumber, with its large leaves, might be a more suitable subject than tomato for scientific studies of the impact of air movement.

5.2.3.3 How might CO_2-use efficiency be improved?

Using Hand's definition as stated above, 100% efficiency is obtained when the CO_2 that is added to the greenhouse atmosphere is just sufficient to maintain the ambient concentration present outside of the greenhouse. Under these conditions, there is no wastage of CO_2 and the amount that is added is exactly equal to the amount taken up and fixed in photosynthesis (Hand, 1984). With this definition, other regimens give different efficiencies and Hand estimated that enrichment to 1000 vpm CO_2 in bright calm weather in winter probably gave an efficiency of CO_2-utilisation as high as 69% while it fell to 5% in dull, windy weather. Hand did not attempt to provide an estimate of the efficiency of adding CO_2 in summer with the vents open but it is evidently not high. Estimates by van Onna (personal communication, not published) suggest the efficiency to be less than 10% under these circumstances.

If the efficiency of CO_2 utilisation is low because natural light levels are low, the efficiency can be boosted either by the use of supplementary lighting or by using an algorithm to help the grower control the CO_2 concentration at the level that gives the highest CO_2-utilisation efficiency. Taken to the ultimate this could take the form of functionality built into a climate control computer. This is the basis of the previously described work carried out by Chalabi et al., (2002a, b) that resulted in a simple set of computer programs for use by growers (Bailey, 2002).

One alternative to the continual addition of CO_2 is to raise the ventilation temperature and enrich only when the vents are closed (or slightly open), while maintaining the external ambient concentration when the vents are more open. However, when this approach was tried with a tomato crop in the UK, fruit quality suffered badly from the elevated temperature (Slack, G., Fenlon, J. S. & Hand, D. W. 1988). Another option is to raise the ventilation temperature for only part of the day and to enrich with CO_2 only during that period. When the vent temperature was raised from 21°C to 27°C for the first four hours in the morning on spray chrysanthemum, and enrichment to 1000 vpm CO_2 was maintained while the vents were less than 10% open, the weight of individual flower sprays was increased. However, they also produced slightly longer pedicels due to the higher day temperature (Cockshull & Fuller, 2001). A similar strategy might merit being tested on other crops.

Another version of partial enrichment is "Intermittent CO_2 Supply" or ICS, a strategy that was proposed in the 1980s in an attempt to get more benefit from CO_2 enrichment. In this technique, CO_2 is supplied in short pulses and in some regimens is supplied only while the vents are closed. The basis of the technique and the early results were discussed by Nederhoff (1994) who also ran experiments to test its effects on the productivity of cucumbers and sweet peppers. Although she found that the observed response was in proportion to the amount of CO_2 supplied, there is a case for testing it again from the perspective of CO_2 utilisation efficiency. In Nederhoff's experiments with cucumber, CO_2 was provided for 8 minutes followed by either 82 or 172 minutes without added CO_2. The amount of CO_2 that was supplied in 8 minutes was related to the difference between the actual CO_2 concentration and the desired concentration of 500 vpm CO_2. In her experiments the average CO_2 concentration was increased by 61 vpm in the 8/82 treatment and it produced a yield increase of 10%.

Temperature has relatively little effect on net photosynthesis at ambient levels of CO_2, but can markedly boost growth when CO_2 is at an enriched level. Langton and Hamer found, for example, that on a single leaf basis, raising the CO_2 level from 350 vpm to 1,000 vpm increased net photosynthesis in *Impatiens* by around 30% at 12°C, by around 70% at 18°C, and by around 103% at 24°C (Defra, 2003). An implication of this is that enriching with CO_2 should (quality and timing permitting) be accompanied by appropriate increases in temperature, or alternatively, CO_2 levels should be manipulated actively in relation to greenhouse temperature. This approach was adopted by Heins *et al.* (1986) who developed photosynthetic optimization equations for chrysanthemum based on CO_2, temperature and PPFD (photosynthetic photon flux density), and used these in a computer-controlled greenhouse to optimise temperature and CO_2 in relation to prevailing PPFD every 15 minutes. This gave significantly greater leaf, stem and total dry weight at flowering. This approach was not taken up commercially at the time, but the concept has recently been extended and promoted by Danish researchers as

"IntelliGrow" and has attracted great commercial interest (Rosenquist & Aaslyng, 2000).

A cause of low CO_2 utilisation efficiency may be the leakage of CO_2 from the greenhouse. One reason for this is wind passing over the structure. As a result measures to reduce external wind speeds are worth considering. All unintentional leaks from the greenhouse should be minimised or blocked with the most likely sites being poorly sealing ventilators. Transparent screens within glasshouses are another means of reducing leakage but they must be removed or withdrawn when the quantity of solar radiation that they are blocking becomes significant. The ultimate variant on this theme is the closed greenhouse that requires active cooling of the air in summer but offers the potential for very high efficiencies and high productivities in the summer months when CO_2 can be provided at 1000 vpm without high losses through open ventilators. The 'GroDome' is an example of such a project in the UK (Lovelidge, 2004) and similar projects in Holland are showing considerable promise.

There are reasons for believing that by diffusing incoming solar radiation, crops might be able to fix a greater proportion of the available radiation because diffuse radiation will irradiate a greater area of leaf surface (Jones, 1983). Improved greenhouse light transmission and more widespread use of film and rigid plastics (as structures made from these materials generally have higher light transmissions than those made from glass) are technologies that may also be placed into this category.

5.2.3.4 The Movement of Water Vapour

The movement of water vapour from within the leaf to the greenhouse atmosphere is governed by the same physical principles that control the movement of CO_2, except that the concentration gradient is reversed, i.e. the atmosphere within the leaf is saturated with water vapour and the concentration gradient is from the inside of the leaf to the external greenhouse atmosphere. From the internal leaf surfaces, water vapour has to pass through the open stomata by day and then across the boundary layer before it enters the general atmosphere of the greenhouse. As the boundary layer is defined as a layer of relatively still air, its water vapour content must inevitably be high because it is adjacent to the saturated atmosphere within the leaf. There is also no doubt that concentration gradients determine the rate of diffusion of water vapour from the leaf and that, especially during the day, the atmosphere of the greenhouse is much less humid than that of the inner leaf surface and the outward gradient is quite steep. Hence, making the boundary layer thinner may not have the impact that is expected. The problem is to predict the effect of air movement upon the water content of the boundary layer. Indeed, Stanghellini (1987, 1988) argues that wind has little effect and that when it does have an effect, it may influence transpiration in a "non-obvious fashion", partly because of its influence on leaf temperature. For these reasons, Stanghellini has advocated controlling transpiration rate as a more sensible basis for the control of the greenhouse environment (Stanghellini, 1987, Van Meurs & Stanghellini, 1989).

Estimates of the boundary layer suggest that it is at least 3mm thick which means that small objects on the surface of the leaf, such as many insects, their eggs and the eggs of their predators and parasites, as well as the spores of fungal pathogens are all likely to lie within the boundary layer in relatively still air.

Consequently, to reduce the boundary layer or at least to influence its water content via air movement or by other means may well be desirable for the biological control of insects or the control of fungal pathogens, except when a high humidity is required for the control measure to work.

5.2.3.5 Air Movement and Plant Diseases

The importance of air movement in relation to the evaporation of water from a leaf is two-fold. First, the rate of water loss is a major determinant of calcium movement to young developing organs and thus to the onset of calcium deficiency in such organs. Secondly, the germination of fungal spores is frequently regulated by the water content of the air and hence their germination on leaves will be affected both by the thickness of the boundary layer and its humidity. As a generalisation, the humidity of the boundary layer is likely to be high because it is the layer next to the internal surfaces of the leaf which are themselves saturated with water vapour. Although there are some doubts about the potential impact of air movement on boundary layer thickness, and its effect on humidity, there are experimental results that show a reduction in fungal infections in circumstances where air movement is deliberately created (O,Neill, 2002). More encouragingly, there are results that show that lowering of atmospheric humidity in the vicinity of crop plants will reduce the incidence of the fungal infection *Botrytis cinerea*. Indeed, O'Neill observed that few spores of botrytis germinated if the humidity was not allowed to be go above 95% RH for more than 3 hours at temperatures from 10 to 20^{o}C, particularly so if a drying-back period of 3 hours spent at 80% RH or less then followed. The recommendation, therefore, was to maintain a RH around the plant of less than 90% and to apply a heat boost with ventilation every night or every time the RH exceeded 90% for 3 hours. It is, however, worth noting that Langton and Hamer (2003) found that heating at night with peripheral heating pipes in small compartments reduced humidity in the air passing through the aspirated screen, but hardly reduced that in the air within the crop canopy. These researchers have stated (Defra, 2003) that improved control of humidity and disease spread will require the direct monitoring or modelling of the air within the crop canopy, and that energy will be saved by promoting efficient air mixing between the canopy and the bulk greenhouse air, so ensuring that disease-related humidity control (which frequently accounts for up to 25% of energy used in protected cropping) is instigated only when absolutely necessary.

5.3 Ascertain the current level of uptake of knowledge that is in the public domain and, if necessary, determine how technology transfer can stimulate better use of the information by growers.

We assess that the current level of uptake of knowledge of the effect of air movement is low. This is largely because the industry does not have ready access to authoritative and independent information on air movement techniques. In the past, a number of very good UK sourced technical booklets were available. Some of the most notable were the 'GrowElectric' Technical Information leaflet 'Fan Ventilation in Horticulture' (1987) and the GrowElectric Handbook 'Ventilation for Greenhouses' (1989). Both of these documents were produced by the predecessor organisation to FEC Services Ltd (the Farm Electric Centre) at the time when it was part of the UK Electricity Council. Whilst these documents still contain valuable background information they must now be viewed as being in need of updating to bring them in line with current commercial practices.

There is also a significant information resource available via the internet. For example a number of American Universities and extension services publish information on the use of fan ventilation and air circulation systems. One of the most notable is the technical note from the University of Massachusetts extension service (www.umass.edu/umext/floriculture/fact_sheets/greenhouse_management) authored by Bartok (2005) that gives some good practical guidelines and information on the correct engineering of horizontal airflow fan ventilation systems.

In the absence of reliable information, growers have a tendency to depend on the following sources for third party information on air movement techniques.

- Equipment manufacturers and suppliers
- Other growers.

Whilst carrying out this study, the authors had discussions with a number of leading growers, especially ones who had taken innovative approaches to the practical application. Without exception, all of these growers had based their approach to air movement on a combination of their own ideas and systems that they had seen in place on other Nurseries, most often in other European Countries such as The Netherlands and Denmark. The conclusions drawn from these discussions were that the only successful systems were based on horizontal air flow using horizontally positioned proprietary air circulation fans (see figure 2 below).

Figure 2 – An example of a horizontal air circulation fan

A number of the growers consulted had also attempted to use vertically mounted paddle fans. Whilst use of this fan configuration is not common in the UK, many growers in northern European Countries (particularly Denmark) use this type of equipment. In their report for HDC Project PC 47, Bailey et al. (1994) specifically mention this type of equipment stating that they do not recommend its use for reasons of poor air distribution. What is interesting is that many of the growers that have tried to use this design of fan have been left less than 100% satisfied with the performance they have achieved.

There is also clearly a lack of knowledge relating to the energy cost/energy efficiency aspects of using fan ventilation systems. Many growers view fan ventilation systems as being expensive to operate because they run on electricity, which is viewed as an expensive energy source. In contrast they see air movement that is stimulated by the use of induced convection currents (from heating pipes) as being virtually cost free because it is a by-product of greenhouse heating. With this in mind there are clearly misconceptions that need to be overcome in order that growers can clearly see the cost/benefits of introducing correctly engineered fan ventilation systems into their production facilities

Having considered the above information, we consider that technology transfer activity is needed to enable growers to fully understand the:

- Practical benefits of air movement and fan ventilation systems.
- Fundamentals of well engineered fan ventilation systems and how they integrate with air movement from heating systems and greenhouse vents.
- Economics and cost/benefits of using fan ventilation.
- Ways that fan ventilation systems can be used with different layouts of greenhouse crops e.g. vine crops, stem flower crops, pot crops grown on benches and pot crops grown on the floor.

In addition, this work should include the results of some of the more recent HDC funded work (most notably PC 47). What is clear is that there is no shortage of information available to include in this activity, and that additional work is not required to make the outcome of the activity highly valuable to the protected cropping sector.

This activity would probably be best carried out by commissioning a grower guide booklet similar to the ones already published on topics like supplementary lighting, micro turbine CHP and slow sand filtration. However it may be worth considering other methods of communication such as information via the Internet and grower meetings/training events.

5.4 Examine the need for further work on air movement / CO_2 use efficiency, paying specific attention to key UK crops and the production systems currently in widespread commercial use. Potential future production/growing systems (i.e. sealed and or low ventilation greenhouses etc.) will also be considered.

As previously highlighted, considerable progress could be made by conducting technology transfer activity that presents current best practice information to growers in the UK protected cropping sector. However, when viewing the medium and long term needs of the sector, it is likely that there will be the need for work to be carried out in a number of new areas. We consider that the most likely areas for work will be as follows:

5.4.1 Sealed Greenhouses

Considerable R&D effort is being carried out in the Netherlands on the concept of the sealed greenhouse. This has now progressed to the point where a commercial operation (named Themato) has built and operated a 14,000m^2 greenhouse for 2 cropping seasons. This commercial operation, backed by significant R&D activity, is practical evidence of the Dutch vision of a fully sustainable greenhouse with zero fossil fuel inputs by 2020 (Van der Veen, personal communication, Greensys 2004 conference).

The Dutch sealed greenhouse project uses a system engineered by a company named Innogrow that centres on the use of ground source heat pumps. However, in addition to this novel energy supply system, it also integrates a whole range of other interesting technologies. Of significant interest is the air movement system which is based on the use of perforated ducts positioned below the crop support troughs (see figure 3 below)

Fig 3 – The air distribution system used in the Dutch sealed greenhouse project.

Key results obtained from this project are energy savings of 20% and a 22% increase in production. The increase in production obtained is an area of significant interest as it was much greater than that predicted by crop scientists working on the project using mathematical crop response models. Whilst it was recognised that the use of a mechanical cooling system (rather than natural ventilation based cooling) would increase the CO_2 use efficiency (and CO_2 levels), this did not fully account for all of the additional response achieved. Discussions with one of the project team (Gelder, personal communication, 2004) revealed that the team believed that the high airspeed at the crop interface (0.2m/s or greater) was in part responsible for the increased performance. This raises some interesting questions regarding the air distribution system used in the closed greenhouse project and its potential role in future greenhouse heating and ventilation systems.

Of greatest interest is the fact that the air distribution method used, and the airspeeds achieved, were in line with the recommendations made by Bailey et al. (1994). Bailey et al. considered the practical use of such systems not to be viable at the time however because of the fact that there was no space available in the greenhouse to accommodate the necessary ducting etc. However, with the advent of raised trough (for edible crops) and bench (for ornamentals) systems there is now room available for the equipment to be accommodated.

With this in mind we believe that it is now time to revisit the methods suggested by Bailey and investigate them alongside the developments associated with the closed greenhouse. It is suggested that a robust way of doing this would be to:

1. Carry out a critical evaluation of the individual component technologies that make up the Dutch closed greenhouse concept (as engineered by Innogrow and used by Themato) and to asses which of the components offer the most value to the protected cropping sector in the UK.

2. Further investigate the use of an advanced air movement system based on the use of perforated air ducting.
3. Carry out on nursery measurements to see how greenhouse climatic conditions (particularly temperature and CO_2 concentration) vary with different designs of air movement & heating system configuration. This study should also integrate studies to see how crop performance and disease levels vary with these systems.

There is a case for carrying out some work to investigate the role of new structures for protected cropping that would have improved energy-saving characteristics allied to enhanced light transmission. Such structures have the potential to require less energy in winter and less ventilation in summer and thereby improve CO_2-use efficiency. Claddings that act to diffuse incident radiation might also be advantageous as they could create more uniform conditions with less shade. In addition they could improve light utilisation partly by diffusing incoming radiation and partly by re-allocating radiant energy to lower leaves under high light conditions. 'Smart' plastic films might achieve some of the above objectives.

5.5 Establish from key R&D workers what new ideas are being developed with reference to air movement/CO_2 uptake requirements and technologies. This section is to include an assessment of the likely commercial value of such new concepts.

Generally there is very little new work being initiated specifically related to air movement and improved CO_2 use efficiency and no new ideas were identified in any of the UK organisations that were consulted. However a wider information search revealed one novel concept that it is suggested will enhance CO_2-utilisation efficiency. This work proposes the supply of green supplemental lighting on the grounds that it can better penetrate a crop canopy to the base of the plant and so stimulate photosynthesis of leaves that might otherwise be in darkness (Kim, Goins, Wheeler & Sager, 2004). In a similar vein, Aikman (1989) suggested redirecting solar radiation to the base of the crop in summer using reflective panels. The integration of a dairy farm operation with the greenhouse production of edible crops has recently been proposed as a means to enhance the value of the energy produced (Scott, Rutzke & Albright, 2005). It could also improve CO_2 use efficiency. It is suggested that such areas of work are watched with interest to see how ideas of this type develop in the future.

The key active workers in the field of air movement in greenhouses and CO_2 use efficiency are listed below. However, as far as we can ascertain, there are no new ideas being developed with reference to the relationships between air movement and CO_2 uptake.

Dr. T. Boulard, formerly of INRA Bioclimatologie Station, Montfavet, France but now of Sophia Antipolis, Antibes & Nice, France

Dr. A. Baille, also formerly of INRA Bioclimatologie Station, Montfavet, France but now of Cartagenia, Spain

Prof. Dr. G.P.A. Bot, Department of Agrotechnology and Food Sciences, Sub-Department of Agricultural Engineering and Physics, Wageningen University, Wageningen, The Netherlands.

Dr S. Hemming, Agrotechnology & Food Innovations, Wageningen University, Wageningen, The Netherlands - Sustainable greenhouse concept.

Dr. C. Stanghellini, Agrotechnology & Food Innovations, Wageningen University, Wageningen, The Netherlands.

Ir. Rijsdijk, Agrotechnology & Food Innovation, Wageningen University, Wageningen, The Netherlands.

6 Conclusions

The key conclusions drawn from this work are:

1. The general level of knowledge on air movement technology in the UK protected cropping sector is low.
2. There is some excellent information available in the public domain (some of it in the form of HDC reports) that can be immediately applied by the UK protected cropping sector.
3. Some effective technology transfer could significantly improve the uptake of effective air movement technology in the UK. This should, as a minimum, take the form of a grower guide supplemented by grower training events.
4. The concept of CO_2 use efficiency is not well understood by many growers. Again the effective communication and technology transfer of previously completed R&D could significantly improve this situation.
5. Many of the concepts associated with air movement and CO_2 use efficiency are not crop/sub sector specific. On that basis much of the work can be carried out in a generic protected crops way.
6. Some further R&D will help growers apply new techniques in a cost effective and profitable nature in the future. This particularly relates to the use of lower energy input systems such as the sealed greenhouse concept.

7 Recommendations for Future Work

The following sub-sections detail our recommendations for work that could be sensibly and cost effectively completed with support from the HDC and be implemented by growers in the UK protected cropping sector in the short and medium term.

7.1 Technology Transfer

This work has strongly identified that immediate benefit could be obtained by a large number of UK growers if they could better understand and utilise the results of previously completed HDC work. In addition the updating of some old publications with new information (and information from other sources) will significantly extend the successful use of the technologies examined in this project by the UK protected cropping sector.

As a minimum it is suggested that the HDC should commission a grower guide on air movement and follow it up with a small number of grower seminars/training events.

7.2 Development Work

Development work in the following areas is proposed.

1. Greenhouse environment data should be collected from commercial facilities to study (and quantify) the extent of problems relating to the uniformity or otherwise of the distribution of air temperature and CO_2. This work should include a number of configurations of heating system, crop type and air movement system design in order that the advantages of well engineered systems can be quantified. The study should also include crop data collection including yield and pest and disease information. Such work will need to be integrated with the ongoing Defra Project HH3611SPC – 'Energy saving through an improved understanding and control of humidity and temperature'.
2. Investigations should be carried out into the development, application and performance into new designs of air movement system. This should particularly concentrate on the ideas initially proposed by Bailey in PC47, and subsequently used in the Dutch closed greenhouse project.

   This work should also consider how the system can be applied to different greenhouse and crop layouts and pay particular attention to situations where supplementary lighting is used.
3. A critical evaluation should also be carried out of the individual component parts that collectively make up the Dutch sealed greenhouse system (as engineered by Innogrow). These components should then be compared with alternative approaches. The outcome of this work should be identification of techniques that may be used to economic effect (either individually or in combination) by the UK protected cropping sector.
4. The previously completed work on CO_2 optimisation should be re-visited and developed in order that it is more appropriate and accessible to UK growers. Whilst the work is based on good R&D it is currently not being used by growers. The work therefore needs to concentrate on better ways of implementing the R&D outputs by growers.

   This work could also include some further work on how CO_2 use efficiency and provide guidelines on how crop uptake might be maximised in circumstances where the amount of CO_2 available is limited. This could include studies on intermittent CO_2 supplies and the option of raising the ventilation temperature for only the early part of the day to reduce CO_2 losses.

7.3 Strategic Research

In the longer term some more strategic studies could be carried out. These are likely to be based on crop science investigations and may concentrate on:

1. Investigating the potentially beneficial effects on CO_2-utilisation efficiency of diffusing the incoming solar radiation before it reaches the crop. This might be combined with work on the benefits of film and rigid plastics. Work in this area could include studies investigating new structures for protected cropping that would have improved energy saving characteristics allied to enhanced light transmission. Much of the North European industry is currently growing in glass-clad structures and research into the benefits (or otherwise) of diffusing and other materials should extend to their use as dynamically operated internal screens (relating to outside ambient conditions).

2. Studies of chlorophyll fluorescence in relation to photosynthetic efficiency and the influence of genotype. Such studies need to look at a wide range of different germplasms (e.g. tomato cultivars and *Lycopersicon* species) and to evaluate photosynthetic performance (including the efficiency of CO_2 fixation) and chlorophyll fluorescence under conditions of stress (e.g. low light, low temperature) as well as under ideal conditions. The efficiencies should be linked to fruit yield, if possible
3. A study to see whether it is feasible to alter the CO_2 conductance by any means, including an increase in stomatal density. This work would need to determine if any increase in CO_2 ingress to the leaf would result in a corresponding increase in water egress that in turn would be harmful in terms of water use (or beneficial in terms of calcium movement). Such studies might also include an assessment of the effect of leaf size on boundary layer thickness.
4. Advances in the power of computers mean it would now be feasible to extend the use of computational fluid dynamics (CFD) to study the effect of induced vertical and horizontal air movement in the presence of a simulated crop. The results of PC 162could also be extended to determine the behaviour of 'dead zones' with strategically located fans. It would also be desirable to test the idea that improved CO_2 distribution could be obtained by injecting the gas within the crop rather than at ground level.

Scientists Interviewed:

Dr S. R. Adams - Warwick HRI
Dr B. J. Bailey - Consultant Horticultural Engineer - previously an employee of SRI Silsoe
Professor W. Davies and colleagues (Lancaster Environment Centre, Lancaster University)
Professor P Hadley (School of Plant Sciences, University of Reading)
Dr P. Hamer - Consultant Horticultural Engineer - previously an employee of SRI Silsoe

Growers Consulted:

Mr R Geater, L.F. Geater & Sons Ltd., Suffolk
Mr C Hynes, Wight Salads Ltd, Isle of Wight
Mr D Findon, W.J.Findon Ltd, Warwickshire
Mr P Pearson, A.Pearson and Sons, Cheshire
Mr T Mills, Grower Manager, Mill Nurseries Ltd, East Yorkshire

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