Project title:	Field storage of carrots: identifying novel techniques
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Project leader:	Mr Tom Will, Vegetable Consultancy Services Ltd
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Location of project:	VCS, Wellbeck; PHS, Warwick; Hobsons, York.
Industry Representative:	Mr Rodger Hobson
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The results and conclusions in this report are based on a mainly theoretical investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

Dr S J Roberts
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GROWER SUMMARY

Headline

In the short-term, the most cost-effective means of reducing straw usage would be to move to a poly-over-straw system, with potential savings of £2000 per ha on straw costs.

Background

UK industry practice is to store carrots for winter and spring marketing *in-situ* in the field, typically covered with a thick layer of straw (with or without a layer of polythene underneath). The aim is to provide insulation against frost damage during the winter and to prevent warming and re-growth in the spring. However, the sustainability of field storage using straw is becoming increasingly challenged – largely due to the high cost and volatile supply of the large quantities of straw required.

Consequently, carrot growers urgently need to examine and evaluate alternative options to current *in-situ* field storage practice.

This project aims to provide the initial step in meeting this need. Novel techniques with similar insulating and light exclusion properties to straw will be identified from a wide range of sectors (including agriculture, construction and chemical industries). All techniques will be evaluated for viability and will be presented to the carrot industry for selection for future testing in 2014.

Summary

The literature on mass heat (energy) transfer in the soil, in insulation layers, and between the soil surface and atmosphere was investigated. The temperature of the soil surface is dependent on the rate of heat/loss or gain from the surface to the atmosphere and the rate of heat transport up and down the soil profile. The deeper layers of the ground/soil act as a reservoir of heat energy. Adding a layer of straw to the surface acts as an insulation layer reducing heat loss during colder periods in the winter and reducing heat gain in the spring. The principles are well understood for the soil/air systems and there is a lot of information on the theory of insulation from the fields of building and engineering. The insulation properties of materials are usually characterised using one or more of the following terms:

- k-value in W/mK is the intrinsic thermal conductivity of a material
- R-value in m^2K/W is the thermal resistance of a material, taking into account its thickness

- U-value in W/m^2K is the thermal transmittance of a system, taking into account all components

Good insulators have low k- and U-values and high R-values.

Characterising the current system is complicated due to the dynamic and thermodynamically unstable nature of the system. Most studies of the insulation values of materials have been done in the context of building and engineering, with measurements under stable conditions. These values do not necessarily provide a good indication of the actual insulation value of straw in the field in the current system. There are three main aspects of the current system that have significant impact on the efficiency of the straw layer as insulation:

Density: as the density of the straw layer decreases, the effective k-value (conductivity) increases, so the insulation value decreases. This means that having a light fluffy layer of straw is less effective as insulation than the same depth of a denser layer of straw.

Forced convection: as the straw layer is not sealed, moving air can penetrate into the surface layers, this air movement increases heat loss, and so the effective k-value increases with increasing wind speed and the insulation value decreases. This effect will also be greater for less dense straw coverings.

Moisture: the presence of moisture in the straw increases the effective k-value and decreases the insulation value. This results from the higher conductivity of water and from the movement of water vapour. Moisture contents of up to 286% were measured in straw samples from field crops. Given that in the UK straw is likely to remain relatively wet throughout most of the winter, the overall insulation value of the straw layer is considerably reduced.

Using soil temperature data, logged at hourly intervals and every 10 cm in the top 40 cm depth of soil under three different surface coverings, we estimated the amount of heat lost from the soil surface on one of the coldest nights (minimum air temp -1.8°C). The total net heat lost from uncovered soil was around 2.25 MJ/m^2 or 39 W/m^2, compared to 3.1 and 2.1 W/m^2 under 10 cm of dense straw and 20 cm of less dense straw. The resulting estimates of the thermal conductivity (k-values) of the straw layers were consistent with those predicted from values in the literature for straw mulches with forced convection.

The role of the polythene layer in the current system is not clear cut. Growers perceive that light-exclusion is important for longer-term storage and discount the insulation value it provides. Apparently, the use of polythene came about as a result of previous ADAS work. There appears to be no information on the effects of light on carrot re-growth, which seems to be mainly temperature dependent. Calculations indicate that insulation value of the polythene sheet may be equivalent to 3 to 5 cm depth of straw. Thus, it may be that the improved storability achieved with polythene may be due to the greater insulation value of the system as a whole.

Another factor reducing the overall insulation value is the effect of the wheelings. When grown on a conventional bed system, wheelings account for approximately 16% of the area. Wheelings are not actively covered with straw, so the incidental covering with straw is thinner. If we estimate that the depth of straw in the wheelings is about half that on the beds, this means that the rate of heat loss will be double for 16% of the area. This thermal bridging effect increases the potential overall heat loss for a field compared to spreading the same amount of straw evenly over the whole area. The resulting surface undulations may also create localised 'frost-pockets'.

Using less straw

Table 1. Comparison of U-values for poly-over-straw vs. straw and straw-over-poly. The moisture content and straw depth represent the measured straw moisture content in a typical strawed crop.

System	Bales per ha	Depth (cm)	Moist. (%)	U-value (W/m^2K)	Material cost (£/m^2)
Dry straw	90	15.5	0	1.42	0.31
Dry straw + poly below	90	15.5	0	1.17	0.36
Moist straw	90	15.5	286	1.97	0.31
Moist + poly below	90	15.5	286	1.52	0.36
Poly top + straw	29	5	0	1.09	0.15

Calculations suggest that making more efficient use of straw by keeping it dry, and eliminating forced convection, would have a major impact on the amount of straw required. This could be achieved by covering the top of the straw layer with a layer of polythene. Results indicate that a 5 cm layer of straw covered with polythene would provide the equivalent insulation to 28 cm of uncovered, wet straw, or 20 cm of uncovered, dry straw. Thus it would seems that potential savings in the amount of straw used of up to 75 % could be achieved by covering the straw with a layer of polythene. It should be noted that these are theoretical calculations, so it is vital that they are tested experimentally, before wide scale adoption in practice. A further benefit of using less straw would be less N lock-up for subsequent crops. Other aspects that would also need to be examined experimentally are:

(i) whether there would be a need for, or the relative importance of also having a layer of polythene beneath the straw to minimise moisture levels in the straw;

(ii) the influence of the emissivity (reflectivity) of the covering layer, particularly for longer-term storage into the spring, i.e. does the cover need to be w hite or reflective to minimise heat gain in the spring ?

It is likely that there would be two main challenges to a poly-over-straw system compared to the current system: (a) anchoring the polythene in place (b) avoiding physical damage/breeches in the polythene that would reduce the insulation value of the covering. There are perhaps a number of approaches to (a):

(i) Apply a second layer of straw over the top of the polythene, this would mean that reduction in the amount of straw used would be lower, but even if the overall amount of straw used was only reduced by a third, this would still achieve potential savings of around £1000 per ha. It is likely that this approach would also deal with (b) by providing direct protection and an insurance layer.

(ii) Cut the polythene into the soil at the time of laying as used in current plastic mulch/film covering equipment.

(iii) Specifically apply an additional thick layer of straw to the wheelings to cover the polythene edges.

(iv) Apply the polythene cover across multiple beds with manual anchoring at the edges.

In addition to dealing with (b) by (i) above, there may be a need to use thicker polythene than the 40 µm thickness commonly used at present. This would of course increase costs. Alternatively, provided it is relatively not too great, some loss could be allowed for by increasing the straw depth.

Given the potential savings that can be made in the amount of straw used, it seems that these are likely to more than offset any additional costs of laying and polythene disposal Reduced amounts of straw could also be combined with other systems, e.g. frost-tolerant varieties with deeper crowns, but experimental data would be needed to quantify the the relative impacts of system components.

Alternative insulation materials

A wide range of alternative materials have the potential to achieve equivalent insulation values to straw, especially if they can be kept dry.

Table 2. Calculated U-values and material costs for selected alternative field storage options.

System	t/ha	Density (kg/m^3)	Depth (cm)	kg/m^2	k-value (W/mK)	U-value (W/m^2)	£/m^2	Notes
Moist straw (90 bales/ha)	45	28.6	15.5	4.43	0.31	1.97	0.31	Current system
SF19 (multifoil)	6.9	-	3.8	0.69	-	0.42	5.00	Exceeds insulation needs.
TLX Gold (breathable)	9	-	3.3	0.90	-	0.91	1.50	Price indication from manufacturer
Poly + Rockwool + poly	5	10	5	0.50	0.044	0.70	2.00	
Poly + 2 layers Vattex + poly	7.5	94	0.8	0.75	0.037	1.96	2.40	
Poly + 1 layer Vattex + poly	3.8	94	0.4	0.38	0.037	2.49	1.20	
Closed PE foam	2.6	35	0.75	0.26	0.037	2.89	1.46	Most easily re-used, with longest life.
Closed PE foam	7.0	35	2	0.70	0.037	1.46	3.68	
Poly + Excel fibre + poly	17.5	35	5	1.75	0.044	0.70	0.80	Cheapest realistic alternative.
Poly + PAS100 GW + poly	200	400	5	20.0	0.060	1.02	0.07	Would exceed N limits
Poly + starch peanuts + poly	3.25	6.5	5	0.325	0.040	0.65	1.72	Difficult to handle
Poly + wood shavings + poly	80	160	5	8.0	0.065	0.94	0.72	Issues with N-lock up
Poly + Bark	107	213	5	10.7	0.060	0.89	1.10	Issues with N-lock up
Foil/Bubble			0.4		n/a	3.75	1.49	
Poly alone		0	0		n/a	6.67	0.05	

Plant-based, straw or straw-like materials are likely to have similar insulative properties to straw if they can be applied at sufficient depth and at sufficient bulk density. However, in most cases they are unlikely to be more efficient than straw, in terms of either volume or biomass required per ha. Also, they would all have the same issues with moisture and forced convection, and N lock-up for subsequent crops. Nevertheless if alternative fibrous materials can be obtained locally at low cost, they may be worth investigating as to the amounts needed to achieve sufficient depth and density to replace straw.

At present, most of the non-straw alternatives are likely to be more expensive than straw, so only become feasible if they can be re-used several times or if the price of straw increases further. It should also be considered that costs of some materials could come down if purchased in the bulk quantities that would be required for carrot field storage. Nevertheless some of these non-straw alternatives would still be worth investigating to have on hand as back-up or additional or supplementary options in case of problems with straw availability.

The cheapest non-straw alternative examined was a layer of PAS100 composted green-waste sandwiched between polythene. However the amount required (up 200 t/ha) would preclude its use due to nitrogen application limits. Bark or wood-shavings sandwiched between polythene are also amongst the cheapest alternatives considered, but the amount required to achieve adequate depth (80 to 100 t/ha) would have much greater impact on N lock-up than straw. Possibly the two effects could be combined, e.g. a mix of green-waste and wood-shavings would counteract each other and effectively provide long-term slow release of N into the soil. However, the dynamics of N release and availability in such a system would likely need further study to ensure there were no detrimental cropping and environmental impacts.

Although relatively expensive initially, closed-cell PE (polyethylene) foam, is worthy of further consideration. This is the material typically used in outdoor sleeping mats and as frost protection for freshly laid concrete. It has the major advantage that, unlike most other materials (including straw), its insulation value is unaffected by moisture. It is robust and would have the potential to be re-used for several years, and would not require covered storage. We could envisage that this could be most readily used in the short-term as a replacement for the polythene layer under a reduced straw layer for later crops. Key factors for its widespread uptake would be the number of times it can be re-used, and the cost of the cost of re-cycling or disposal.

Excel fibre (http://www.excelfibre.com/) in a polythene sandwich is another alternative that could become feasible as a single-use option if straw costs increase. This is an industrial 100% re-cycled cellulose-fibre type product similar to one that has been developed as loft insulation (Warmcel) and with similar insulation properties.

Conclusions

- The insulation properties of straw are affected by bulk density, moisture content, and forced convection.
- The current carrot field storage system of straw or straw-over-poly make inefficient use of the potential insulation value of straw.
- Spreading the same amount of straw evenly across the entire field (including wheelings) may be more efficient than just applying to beds and reduce overall heat loss by around 6%.
- The insulation value of the polythene in straw-over-poly is not negligible, but its value for light exclusion has not been established. This needs to be investigated.
- In the short-term, significant reductions in straw use (possibly up to 75%) can theoretically be made by covering the straw with polythene to keep it dry and prevent forced convection. This needs to be confirmed experimentally.

- A range of potential alternatives to straw have potential to provide equivalent or better levels of insulation than the current system.
- The material costs for most non-straw alternatives are higher than the current cost of straw and only become cost-effective if they can be re-used or if straw prices increase significantly.
- At least two non-straw alternatives are worth practical experimental investigation: closed-cell PE foam and Excelfibre in a polythene sandwich. Respectively, these are highly re-usable and at the lower end of the cost scale.
- Closed-cell PE foam could be used as a supplement in the current system if straw is in short supply.
- Some non-straw alternatives could possibly be combined to improve their feasibility.

Financial Benefits

The area of carrots stored under straw is estimated at around 3-4000 ha per annum. Current estimates for the costs of straw-based field storage systems are around £30 per 500 kg Hesston bale (delivered to field), applied at 80-120 bales/ha. With application and removal included, the technique costs around £4000-5000 per ha on top of crop production and harvesting costs. However, almost as important as cost is the vulnerability of straw supply.

Theoretical calculations of the insulation values achievable indicate that a reduction in straw usage of up to 67% could be achievable by moving to a poly-over-straw system. This could amount to a saving of £2000 per ha, equivalent to at least £6 million per annum for the industry as a whole.

Action points for growers

This project was predominantly a desk-study to evaluate potential options, therefore the main action point is to consider funding further work to validate the theoretical calculations and demonstrate the options with the most potential:

- Growers should consider funding experimental work to (a) validate the theoretical calculations reported here; (b) to confirm the potential of the most feasible alternatives so the information is readily available in case of straw price increases or supply issues; (c) understand the effects of light and light-exclusion on spring re-growth and quality; (d) evaluate the effect of pre-conditioning (pre-chilling) prior to covering; (e) develop a model that can be used to accurately predict insulation/straw requirement for different situations.

SCIENCE SECTION

Introduction

UK industry practice is to store carrots for winter / spring marketing *in-situ* in the field, typically covered with a thick layer of straw (with or without a layer of polythene underneath) to provide insulation against frost damage during the winter and to prevent warming and re-growth in the spring. However, field storage using straw (either with or without polythene) is becoming increasingly challenged as a sustainable technique – largely due to the high cost and volatile availability of straw, but also due to agronomic issues such as nutrient lock-up from the decomposition of incorporated straw after carrot harvest. With the continued development of straw-fired biomass plants, increasing pressure on cereal farmers to re-incorporate organic matter rather than remove it as straw, the volatility of the cereal market and the effects of climate change, use of short strawed varieties, supplies of straw are likely to become both more expensive and erratic in future years.

Therefore, carrot growers urgently need to examine and evaluate alternative options to current practice – either by moving from field storage to the more continental European refrigerated storage methodology or finding alternative strategies for *in-situ* field storage. With existing refrigerated storage techniques requiring considerable adaptation and evolution to fit the UK requirements, the best short-term option for carrot growers is to examine and evaluate alternative *in-situ* field storage options.

This project therefore aims to identify a range of novel techniques that have the potential to replace or reduce the amount of straw used for *in-situ* field storage of carrot crops for winter / spring marketing. The primary output of the project will be a list of potential options that can be advanced to field trials in 2014

The specific objectives of the project were to:

1) Establish and document the heat transfer and light exclusion principles critical for field storage of carrots.
2) Benchmark the heat transfer and light exclusion characteristics of current straw (+/- poly) techniques to compare to novel methods.
3) Identify novel techniques for replacing or reducing straw usage with alternative insulators or methods.
4) Evaluate the potential efficacy and cost of the identified techniques compared to straw systems.
5) Compile and present a list of the most promising techniques to BCGA R&D committee for discussion and selection for potential field trials 2014.

6) Report and disseminate results to the carrot industry.

The area of carrots stored under straw is estimated at around 3-4000 ha per annum. Current estimates for the costs of straw-based field storage systems are around £25 to £30 per 500 kg Hesston bale (delivered to field), applied at 84 to 125 bales/ha. With application and removal included, the technique costs around £4000-4500/ha on top of crop production and harvesting costs. This is a significant and annually increasing additional cost to production which growers have to bear – and which is not sufficiently reflected in additional returns from customers for stored carrots. However, almost as important as cost is the vulnerability of straw supply – particularly with the effects of changing climate on cereal straw production, but also due to the increasing demands on the available straw supply by other agricultural or energy sectors.

If carrot growers can replace or reduce the amount of straw required to achieve the same insulating effect, significant savings could be generated. For example, a 10% reduction in straw would result in a £300/ha saving equivalent to a £1million saving per annum across the industry. However, it should be noted that although some of the savings generated by using less straw will be off-set by the costs of an additional technique, there will also be a benefit in being less reliant on a volatile supply of raw material.

Materials and methods

Information was gathered by conducting on-line searches of both general information and the scientific literature. Searches were made in the fields of crop production, soil sciences, ecology, building and engineering. A carrot crop physiologist was also consulted directly, together with some suppliers of potential alternative materials.

Visits were made to three strawed crops: two in Scotland and one in Yorkshire. The depth of straw covering was measured and grower information on the number of bales used in the field noted. Samples were also collected and transported to the laboratory for measurement of moisture content and bulk density.

Based on information in the literature and using the estimated/measured values of bulk density and moisture content, the effective insulation values (U-values) were calculated for different variation of the current strawing systems (i.e. with/without polythene).

Three soil temperature loggers were placed in different beds in a single field of recently strawed carrots in Yorkshire at the beginning of November. The loggers used probes that recorded the temperature at 10 cm intervals along their 50 cm length. The loggers were powered by solar panels and reported data to a central web-site automatically on a daily basis using the mobile phone network. The probes were inserted in the centre of the beds, with top 10 cm above the soil, so that the upper sensor measure air temperature at 10 cm above soil level, the 10 cm sensor measured temperature at the soil surface, etc. One probe was placed in a bed covered with the typical layer of straw in the majority of the field, about 20 cm depth of low density straw from a conventional combine; one was placed in a neighbouring bed covered with 10 cm depth of high density thin, chopped straw from a rotary combine; and one probe was placed in a bed from which the straw was cleared within a radius of about 2 m from the probe.

Data from the soil temperature probes was used to estimated actual heat loss and thereby calculate the effective U-values of the straw coverings.

A list of potential alternatives to the current system was drawn up and subject to an initial evaluation of their feasibility. For a number of the most feasible alternatives, k-values were obtained or estimated and used to calculate the effective overall U-value of the system.

Heat transfer and light exclusion principles critical for field storage of carrots

Temperature and humidity

The overall aim of carrot field storage is to provide a continuity of supply of high quality carrots during the period November to June. The ideal requirements for successful long-term (7 to 9 months) storage of mature carrots are a low temperature (0 to 1°C) and high relative humidity (98-100%). The high humidity is required to avoid water loss and maintain skin quality and crispness, and the low temperature is required to prevent re-growth and minimise respiration (even at 0°C some measurable respiration can occur (Suslow, T.V., Mitchell, J. & Cantwell, M)). The base (minimum) temperature for carrot growth has been reported to be as low at 1°C (Suojala, Tehri 2000; Benjamin & Aikman 1995; Brewster & Sutherland 1993).

Pre-storage growing conditions are also reported to have an impact on the storability of carrots: pre-exposure to low temperatures (below 6°C) induces cold acclimation and increases the levels of anti-freeze proteins in root tissues (Gómez Galindo *et al.* 2005). Thus, carrots are likely to store better and be more resistant to frost damage if pre-conditioned by exposure to low-temperatures. However, the impact of such pre-conditioning on eating quality, is not known.

Field storage of carrots is necessarily a balancing act/trade-off that aims to approach ideal storage conditions. During field storage we might consider that the overall aim/target is to maintain the surface temperature of the soil in the range 0-4°C during the storage period with soil moisture at or close to field capacity. It is critical to prevent frost/freezing damage to roots during the coldest parts of the year, but due to the presence of solutes in the soil water and solutes and specific anti-freeze proteins in carrot roots, tissues will not freeze and freezing damage will not occur until the soil temperature is below 0°C.

For long-term storage of carrots until May, there is not only a critical need to prevent frost/freezing damage during the winter months, but also to keep the carrots as cool as possible to prevent re-growth, the initiation of flowering and development of 'woody' tissues in the spring period.

We can summarise the main requirements for field storage of carrots as aiming to prevent frost damage during the winter months by reducing the rate of heat loss from the soil and to prevent re-growth in the spring by reducing the rate of heat gain. Both requirements can be satisfied by adding a layer of insulation on top of the soil surface.

Light exclusion

According to the Assured Produce Guide (2013): "Spring re-growth of carrots is light dependant; thus the use of black polythene helps retard this". However, we have been unable to find any evidence for this this statement in the scientific literature and there seems to be no information on the impact of light, or light exclusion on carrot storage. This was also confirmed by consultation with an experienced carrot crop physiologist previously at HRI Wellesbourne (Benjamin, pers. comm). This does not mean that light exclusion does not have any impact, only that it has not been studied. We suspect that while light exclusion itself will not prevent re-growth, the absence of light will have impacts on phyto-hormone levels and hence have other impacts on plant physiology and root metabolism.

Soil temperature and energy balance

In trying to assess the requirements of any insulation materials used for field storage of carrots we first need to understand the soil energy balance and the factors that are most important in determining this.

We can consider the temperature of an object or mass as a measure of the amount of heat energy contained or stored in it, this energy is measured in Joules (J). The amount of heat required to raise the temperature of a unit mass of a material by 1 K (or 1°C) is called the specific heat capacity, and is usually measured in J/g.

Energy transfer processes

Energy or heat transfer to/from and within the soil occurs via four basic mechanisms. Heat flux (or flow) is measured in Watts (W) or Joules per second.

Conduction

Conduction is heat transfer through matter as a result of the transfer of kinetic energy at the molecular level, due to a temperature gradient. Energy 'flows' from molecules at a higher temperature to molecules at a lower temperature. Conduction is the most important means of heat transfer within soils.

Radiation

Radiation is the transfer of energy to or from a body by means of electromagnetic radiation. All matter with a temperature above absolute zero (i.e. 0 K or -273.15°C) emits radiation. If an object radiates more energy than it receives from other sources, it will cool, and vice versa. Radiation is important in the transfer of heat to/from the soil surface.

Convection

Convection is the transfer of heat energy from one location to another as a result of the movement of fluids (e.g. air or water). The fluid is heated and physically moves from one place to another taking the heat energy with it. As air is a poor conductor, convection is the main means of heat transport in air.

Latent Heat

Latent heat is the transfer of energy due to a phase change in a solid, liquid or gas. When water condenses, or freezes, the temperature of the surrounding environment rises because latent heat is changed to sensible heat. Likewise, when water evaporates or ice melts, the temperature of the surrounding environment drops as sensible heat is changed to latent heat. Latent heat is the chemical energy stored in the bonds that hold the water molecules together as either a solid or liquid, and sensible heat is the heat can be measured with a thermometer.

Table 1 shows the amount of heat consumed or released per unit mass for water for each of these processes in comparison to its specific heat capacity. It is clear from these values, that much more energy is required to evaporate water, or melt ice (or is released when water vapour condenses or freezes) than is required to heat (or cool it) by 1°C. Thus, we can calculate that the energy released when 1 g of water freezes is equivalent to raising the temperature of 4 g of water by 20°C

Table 3. Basic thermal properties of water.

Property	Value (J/g)	Explanation
Specific heat capacity	4.18	the amount of energy needed to raise the temperature of 1 g of water by 1°C, or the amount of energy released when 1 g of water cools by 1°C
Latent heat of fusion	333	the amount of energy needed to melt 1 g of ice, or the amount of energy released when 1 g of water freezes.
Latent heat of vaporisation	2260	the amount of energy needed to evaporate 1 g of water, or the amount released when 1 g of water condenses.

Soil energy balance

At a certain depth below the surface (usually around 10 to 15 m) the ground/soil temperature remains almost constant and approximately equal to the mean air temperature (8 to 12°C depending on location in the UK). Even at a depth of only 1 m below the surface, the fluctuations in soil temperature are relatively small. Effectively, the deeper layers of the soil/ground provide a reservoir of heat energy, the temperature then at the soil surface depends on the rate of heat gain or loss to the atmosphere and the rate at which heat is transferred up and down the soil profile.

Within the soil:

Conduction is the most important means of heat transfer up and down the soil profile (De Vries & Afgan 1975), although convection and radiation may also play a role depending on conditions. The following is derived from several sources but particularly (Snyder & Paw U 2000).

Fourier's law is used to describe conduction, so that for small depth changes:

$$G \approx -k(dT/dz)$$

where G is the soil heat flux density (W/mK), k is the apparent thermal conductivity, T is the temperature and z is depth.

This is combined with the conservation of heat equation:

$$c_v \, dT/dt = dG/dz$$

to give:

$$dT/dt = Dd^2T/dz^2$$

where thermal diffusivity $D = k/\rho c = k/c_v$

ρ = density, c = mass heat capacity, c_v = volumetric heat capacity, t is time

Soils are made up of sand and minerals, organic matter, water and air. The overall thermal conductivity of a soil therefore depends on the conductivity of the individual components and the proportion (by volume) of the soil they comprise. In practice it is dependent mainly on the bulk density of the soil and the soil water content. Increasing the bulk density of the soil will increase the conductivity of the soil. Increasing the moisture content of a soil will increase both its thermal conductivity and its heat capacity (see Table 2). Their ratio, the thermal diffusivity (D) generally initially increases with increasing moisture content up to a maximum and then declines slightly with further increases in moisture content (Arya 2001). It is mainly the value of thermal diffusivity which determines how quickly or slowly temperature changes are transmitted up/down the soil profile. Typical values for different soils are shown in Table

2, where it is clear that sand and sandy soils have the highest values for conductivity and diffusivity. This immediately indicates that given the same set of environmental conditions, on a cold night the soil surface temperature of sandy soil will be higher than in other soils, as heat will be transferred more quickly up the soil profile to replace heat lost from the surface.

Table 4. Thermal properties of three basic soil types in relation to moisture content.

Soil type	Water %	Conductivity (W/mK)	Volumetric Heat capacity (J/cm^{3}K)	Diffusivity (D) (x 10^{-7})
Sand	0	0.29	1.25	2.3
	20	1.8	2.09	8.6
	40	2.2	2.93	7.51
Clay	0	0.25	1.25	2.00
	20	1.2	2.09	5.74
	40	1.6	2.93	5.46
Peat	0	0.06	1.46	0.41
	40	0.13	3.14	0.41
	80	0.71	4.81	1.48

Heat is also transferred through the soil via moisture movement, e.g. as water percolates down through the soil due to gravity and along thermal and osmotic gradients. More complex models are required to describe heat transfer in soils that take this into account, and are needed for precise modelling of soil heat transfer.

At the surface:

Heat is gained or lost from the soil surface to the atmosphere by several different energy transport processes, and the surface energy balance is usually given by:

$$G = Rn - LE - H$$

where:

Rn = net radiation

G = soil heat flux

LE = latent heat flux

H = sensible heat flux (transfer of heat from or to a surface by conduction or convection) – mostly due to convection as air is a poor conductor and is also affected by wind speed.

Furthermore the net radiation is calculated as:

$$Rn = Rsi - \alpha Rsi - Lo + Li$$

where:

Rsi = solar irradiance, incoming short-wave;

αRsi = reflected solar irradiance, short-wave, alpha is the albedo or reflectivity of the surface, and changes with the angle of the sun;

Lo = longwave out (depends on emissivity and temperature) = $\varepsilon\sigma T^4$

ε = *emissivity*, σ = Stefan-Boltzmann constant (5.67 x 10^8), T = temperature in Kelvin

Li = longwave in from the sky

During the day the net incoming radiation, Rn, is usually greater than heat lost by evaporation, LE, and sensible heat, H, and the soil gains energy (heats up, the value of G is positive). At night Rn is usually negative and the soil loses energy (cools down, the value of G is negative).

A note on frost penetration

A main concern expressed by growers is about 'frost penetration' into the soil. When talking about frost penetration or frost depth, we mean the depth at which groundwater in the soil is frozen. This is often conceptualised as the movement of 'cold' into the soil and down the soil profile, when actually it is the result of movement of heat upwards and its loss from the soil surface. Effectively it is the advance of the (below) zero-degree isotherm through the soil, the rate of advancement is slowed by the release of latent heat during freezing, and hence is slower in soils with a higher water content, than in soils with a lower water content. The presence of ions in the soil water causes a depression in the freezing point, so that the freezing front advances slightly behind the zero-degree isotherm.

Characteristics of the current field storage system

Straw

The current field storage system in typical use is to cover the crop with a layer of wheat straw during October before the onset of any significant frost events/cold weather. Growers are usually aiming to have all field stored crops covered by the beginning of November, so the timing of the start of strawing is determined by operational logistics, with an allowance for delays. This will mean that in many cases the soil temperature is significantly higher than the ideal temperature for storage at the time of covering, and also means that the there is no pre-conditioning to improve cold tolerance.

Straw is applied on a bed-by-bed basis and the primary variable is the depth of straw applied. The target depth is adjusted according to location (colder → deeper), and planned storage duration (longer → deeper). The required depth is achieved by varying the number of bales applied per ha, also taking into account straw 'quality'. Growers/strawing contractors consider that they are aiming to produce a light 'fluffy' layer of straw over the beds. A certain amount of straw falls off the beds into the wheelings and is also redistributed by the wind, so that wheelings between beds also become covered, but with a shallower depth of straw than the main body of the beds. There is generally a lower limit to the number of bales per ha needed to achieve uniform/complete coverage of the crop. At the time of straw laying the crop still has green foliage, this combined with the carrot type/crown level and straw 'quality' may result in a significant air gap between the soil surface and the bottom of the straw layer.

Characterising the properties of the straw layer in the current system in relation to its impact on soil temperature is more complex than might first be imagined. At the simplest level we shall consider the purely insulative properties of the straw layer.

Much of the literature on the insulative properties of materials comes from the fields of building and engineering. In comparing the insulative values of different materials three measures are generally used (Table 3). One important aspect to be aware of when comparing materials is that the R-value and U-value take into account the thickness of the material, whereas the k-value does not. Good insulators will have relatively low k-values, low U-values, and high R-values, but note that a material with a relatively high k-value can give equivalent insulation to a material with a lower k-value by using a greater depth. U-values are usually used and calculated for the combined effect off all the components in a structure, i.e. they applied to the system or structure as a whole whereas R- and k-values are applied to individual components or materials. Thus when estimating the overall U-value for a system account is taken of the resistance to heat transfer that occurs at surfaces and across air layers, in addition to the intrinsic properties of the materials. It should also be noted that all of the units are for a temperature difference of 1 K (1°C), so e.g. a U-value of 1 means that 1 Watt is lost per square metre of surface per degree temperature difference, so that if the temperature difference is 10 degrees the rate of heat loss will be 10 times greater. It is also important to note that many of the values for materials presented in tables, etc. found by searching on-line give values in Imperial (American) units, rather than SI units. SI units are used throughout this report.

Table 5. Measurement units used in the context of insulation calculations.

Measure (units)	Explanation
U-value (W/m^2K)	Thermal transmittance, coefficient of heat transmission, a measure of heat loss through a structural element / component. It is calculated as the rate at which heat transfers through 1 square metre of a structure, where the temperature difference between the inner and outer face is 1 degree Celsius. The U-value is the reciprocal of the sum of R-values of all the individual components in a structure i.e. including air gaps, surfaces etc. The lower the value the better the insulation value of the structure. $U = 1/(R_1 + R_2 + R_3 + ... R_n)$ or for single component $U = k/l$
k-value, also lambda, λ (W/mK)	Thermal conductivity. The rate at which heat is conducted through a material, measured as Watts per m2 of surface area for a temp. gradient of 1 K per m of thickness ($W/m^2K/m$) = W/mK The k or lambda value does not take into account the actual thickness of a material The lower the value the better the insulator.
R-value (m^2K/W)	Thermal resistance. Ratio of temperature difference across an insulator and heat flux through it. Measured in m^2K/W, equal to the thickness in m divided by the conductivity, lamba, I.e. R = thickness / lamda = l / k The R-value takes into account the thickness of a material. The higher the value, the better insulator.
Emissivity	Is the relative ability of the surface of a material to emit energy by radiation, compared to a black body at the same temperature.

Determining the ther mal conductance or resistance of a material or structure requires specialist equipment, and is usually done under very specific defined, (constant temperature) conditions for which there are international standards, but not always agreement. Still air is a poor conductor of heat and is therefore one of the best insulators as long as heat transfer by convection is minimised. To minimise convection, the air space should be small and this is the basis of most insulation materials used in buildings – the materials (whether it be rock-wool, glass-wool, polyurethane foam etc.) trap **small** pockets of air and so achieve effective thermal conductivity values approaching that of air. This is why in double glazing there is no benefit from increasing the width of the air gap beyond a certain value, and why, in houses with a cavity wall, the cavity needs to be filled with insulation material to maximise insulation. Some typical values of k for some common materials are given in Table 4.

Table 6. Values for the thermal conductivity (k-value) of some common materials.

Material	k-value (W/mK)
Still air	0.024
Water (0°C)	0.563
Water (20°C)	0.596
Snow	0.05 to 0.25
Ice	~2
Sand (dry)	0.29
Sand (40% moisture)	2.2
Peat (dry)	0.06
Rockwool insulation	0.04
Straw bale 75 kg/m3	0.052

There is very little reliable information on the insulative properties of a layer of straw in the field. Most of the values available in the literature are for densely packed straw bales, as used in the construction of straw-bale houses and buildings, and even here there is some disagreement about the reliability of the values obtained with different measurement systems. Examples of some of the generally accepted and measured values are given in Table 5.

Table 7. Some measured values of the thermal conductivity of straw at different densities and from different sources.

Material	Density (kg/m^3)	k-value (W/mK)	Depth (cm)	Source
Straw bale, parallel	75	0.057	38.5	http://www.sbi.dk/download/pdf/jma_slides_halmhuse.pdf
Straw bale, perpendicular	75	0.052		
Straw bale, parallel	90	0.060	38.5	
Straw bale, perpendicular	90	0.056		
Straw	12.5	0.300	?	(Paulsen 2010)
Straw	14	0.112	12	
Straw	19.9	0.055	12	
Straw	26.1	0.050	12	
Wheat straw (stable)	11.8	0.088	6.1	(van Donk & Tollner 2000a)
Wheat straw	17	0.060	6.1	
Wheat straw	11.8	0.099	14	
Wheat straw	17	0.064	14	
Wheat straw (unstable)	11.8	0.109	6.1	
Wheat straw	17	0.062	6.1	
Wheat straw	11.8	0.127	14	
Wheat straw	17	0.065	14	
Forced convection:				(van Donk & Tollner 2000b)
Wheat straw	12	0.21 to 0.38	7	
Wheat straw	14	0.35 to 0.59	16.3	

Attempts to obtain meaningful measures of the conductivity of straw as used in the field are fraught with difficulty. Some values obtained by the Danish Technological Institute (Paulsen 2010) clearly indicate that increasing the density of the straw layer gives lower conductivity. Their results suggest that at densities greater than about 20 kg/m^3 the thermal conductivity plateaus at a k-value of about 0.05 W/m.K; these values seem to have been measured under thermally stable conditions and the value is similar to those reported for much denser straw bales, but lower than some other reported values (no doubt due to differences in measurement methods) (see Figure 1).

Figure 1. Relationship between thermal conductivity and straw density. Triangles are from van Donk (2000a). Squares are from Paulsen (2010).

The most useful insights we have found have come from research published by van Donk (van Donk & Tollner 2000a; b). The research, done in N. America, was focussed on the effects of mulch layers (e.g. wheat straw and other mulch materials) on soil temperatures. They identified the problem that conventional measurements of the thermal conductivities of straw-layers (between plates in thermally stable conditions, warmer at the top than bottom that provide a single k-value), under-estimate the thermal conductivity under more thermally unstable conditions (warmer at the bottom than the top). In particular they (van Donk & Tollner 2000a) identified several key aspects:

Under thermally unstable conditions:

- free convection is important and and increases with decreasing mulch density;

- the thinner the layer and the more void space the more important thermal radiation becomes as a means of heat transport;
- for a given material the apparent thermal conductivity (k) is greater than under thermally stable conditions;
- the increase in k is inversely proportional to density and thickness

In a further paper (van Donk & Tollner 2000b), they went further to examine the effect of forced convection (i.e. the effect of air movement, wind) on apparent conductivity (see Figure 2. Their results demonstrated clearly that the apparent conductivity generally increased with increasing air speed due to penetration of moving air into the surface layer, although for the thicker layer of straw there was a minimum at 1 m/s attributed to interactions between the straw and convection (free vs. forced). (Flerchinger, Sauer & Aiken 2003) also showed that accounting for the effects of wind on convective transfer was needed to accurately simulate the effects of crop residues on soil temperatures.

Figure 2. Effect of wind speed on apparent k-values for a layer of straw. Approximate values extracted from van Donk (2000b).

Measurement of straw density in the field

The bulk density of the straw layer was estimated in two ways: (a) by calculation based on the number of bales applied and the measured depth in the field; and (b) by measurement of the actual bulk density in the laboratory of straw samples collected from the field. The calculation for (a) used was:

$$\text{Density (kg/m}^3\text{)} = \text{CF x (No Bales x Wt per bale)/(depth/100 x 10000)}$$

where Wt per bale is in kg, and depth is in cm, and CF is a correction factor to take account of wheelings. This was calculated on the basis that wheelings occupy 16% of the total area and have about half the depth of straw as the beds, so CF = (1 – 0.16/2)/(1 – 0.16) = 1.095

For (b) the straw sample was placed in plastic box of known volume, weighed and allowed to air dry over several weeks with repeated weighing every few days, until there was no further weight change. The bulk density was then calculated on the basis of the final dry weight divided by the volume.

For (a) we initially assumed an average weight per bale of 500 kg but invariably this resulted in values for (a) which were very much greater than the values obtained by laboratory measurement. Changing this value to 400 resulted in values which were much more in line with the lab-measured (b) values. One of the main difficulties was in accurately measuring the depth of the straw layer (both in the field and in the lab), as especially for field values, a 1 cm change in the depth can have large influence on the estimated density.

The results of the estimated and measured values are shown in Table 6. Based on the calculated field estimates (a), all of the densities achieved are in the range where the k-values plateau out according to Paulsen (2010), whereas based on the lab measurements (b) it appears that shortly after application, the density was sub-optimal for the conventional straw at site 1.

Table 8. Estimated field density (a) and measured density (b) and moisture levels in straw samples from field crops.

Straw source	Straw type	Bales/ha	(a) Field		(b) Lab		Moisture	
			Depth (cm)	Density (kg/m3)[1]	Depth (cm)	Density (kg/m3)	% wet wt.	% dry wt.
1	Conventional	84	20	18.4	13.5	12.7	40.4	67.9
1	Rotary	84	10	36.8	9.5	26.2	42.9	75.1
2	Conventional	70	11	27.9	12	20.8	72.5	264.0
3	Conventional	90	15.5	25.4	13	28.6	74.1	286.2

[1]Assumed wt of bale: 400 kg.

Straw plus polythene

For longer term storage, growers use a layer of black polythene beneath the straw-layer. It is considered that the main purpose of the polythene is to exclude light which prevents re-growth in the spring, and that it has little or no insulative value. However, as indicated earlier, we have been unable to find any information on the effects of light on carrot re-growth, and would question it's direct benefit in this respect. It is also not correct to consider that the polythene has little insulative value. Calculations indicate that adding a layer of polythene potentially has an insulative value at least equivalent to a depth of about 5 cm of dry straw (at minimum k-values). Indeed anyone who has had cause to make use of a polythene survival bag will be aware that the insulative benefit is not negligible. This effect depends on there being a layer of air underneath the polythene, if the polythene is in direct contact with the soil the benefit will be reduced. The layer of polythene provides a barrier to heat transfer by preventing air and vapour movement.

Effect of moisture

Most of the literature and calculations found in building and engineering literature are all based on dry insulation materials, and assuming that there are vapour barriers in place. All of the measurements/calculations/estimates of the insulation value of straw referred to previously are based on dry straw. However, under the current system in the UK the straw is exposed to the atmosphere and so will acquire moisture as a result of condensation and snow/rainfall. Moisture will also be lost from the straw layer through evaporation and drainage (either directly into the soil or drainage into the wheelings when over plastic). This moisture in the straw layer will have several impacts compared to dry straw:

i. increasing moisture will increase the overall thermal conductivity (k-value) for the layer;
ii. increasing moisture will increase the thermal capacity of the layer;
iii. movement of water vapour will increase heat transport upwards;
iv. under evaporative conditions, heat loss from the layer will be greater (latent heat of evaporation);
v. in freezing conditions the rate of progress of the zero-degree isotherm down through the layer will be reduced (latent heat of fusion), but note that as ice has a higher conductivity than liquid water, once frozen, the heat lost would be greater.

In the late spring the cooling effect of (iv) could be beneficial. Likewise (v) could be beneficial under certain specific weather conditions. Understanding these contradictory effects would require modelling and/or data collected over a long period. However, on balance, and based on work in the building and engineering literature, we suspect that the overall improvement insulation value of keeping material dry outweighs any potential short-term cooling effects.

In addition, the presence of moisture will have an additional consequence as it will promote the more rapid degradation of the straw, effectively reducing the thickness of the layer and reducing its effective insulation value.

For the purposes of calculations of the effective conductivities, a correction for moisture content of 0.03 x %moisture was used (Riha *et al.* 1980; Bussière & Cellier 1994).

Calculation of insulation values of systems

For overall comparison of the i nsulation values of different systems we use the U-value (in units of W/m^2K), this provides the rate of heat transfer (in Watts) per square metre per degree temperature difference. Lower values indicate better insulators. To c alculate the overall U-value we first calculate the R-values for each layer in the s ystem, based on the thermal conductivity (k-value) and the thickness of the the layer (l), e.g.:

k-value = 0.22 W/mK

thickness = 20 cm

R-value = (20/100)/0.22 = 0.044

If the system consists of just a single layer then the U-value is calculated as:

U-value = 1/R = 1/0.044 = 22.73

If the system consists of several layers then the U-value is calculated as:

U-value = $1/(R_1 + R_2 + R_3 ...R_n)$

Some example calculations of the U-values, based on the measured values of straw depth, density and moisture are shown in Table 7.

Table 9. Estimated insulation values of current straw systems, based on measured densities and moisture values

System	Bales per ha	Depth (cm)	Density (kg/m^3)	Moisture (%)	Min.[c] k (W/mK)	R(straw)	R(poly)	U-value (W/m^2K)
Dry straw	84	20[a]	12.7	0	0.30	0.67	-	1.50
	84	10[a]	26.2	0	0.22	0.45	-	2.20
	70	11[b]	20.8	0	0.22	0.50	-	2.00
	90	15.5[b]	28.6	0	0.22	0.70	-	1.42
Moist straw	84	20[a]	12.7	67.9	0.32	0.62	-	1.60
	84	10[a]	26.2	75.1	0.24	0.41	-	2.43
	70	11[b]	20.8	264.0	0.30	0.37	-	2.72
	90	15.5[b]	28.6	286.2	0.31	0.51	-	1.97
Moist straw over polythene	84	20[a]	12.7	67.9	0.32	0.62	0.15	1.29
	84	10[a]	26.2	75.1	0.24	0.41	0.15	1.78
	70	11[b]	20.8	264.0	0.30	0.37	0.15	1.93
	90	15.5[b]	28.6	286.2	0.31	0.51	0.15	1.52

[a] Initial depth (a few days after laying).
[b] Settled depth (six weeks after laying).
[c] Minimum k-value, without forced convection.

Estimation of heat-loss and U-values from recorded data

Data from the three data-loggers placed in a strawed carrot crop in Yorkshire, shortly after the straw had been appl ied, were used to es timate the ac tual heat l oss from the s oil that occurred on one of the coldest nights (18 to 19 Nov 2013) when the air temperature dropped to -1.8°C, under the three different coverings (none, rotary, conventional). The full data is shown in the Appendix. The loggers recorded temperature in the soil profile at intervals of 10 cm intervals. The initial and final (minimum) temperatures at each point in the profile were used to obtain an average drop in temperature for each 10 cm depth of soil. Then, using an estimated volumetric heat capacity for a sandy soil at field capacity (Snyder & Paw U 2000) of 3.27 MJ/m^{3}K, the heat loss from each 10 cm layer was calculated. The sum of the losses in all layers was then taken as the total heat lost from the soil surface. Results are shown in Table 5, and c learly show the r eduction in heat loss with the straw covering. It s hould be noted that the bare area was within the s trawed field and was only about 2 m in diameter; therefore this heat l oss value will be an under -estimate of the heat l oss from a total ly uncovered field due to horizontal conduction of heat within the s oil from the s urrounding covered areas. The estimated U and k-values from this data are consistent with the minimum k-values predicted from the w ork of (van Donk & Tollner 2000b). They also demonstrate clearly that, as predicted, the m ore densely packed layer resulting from the rotary combine has a lower k-value than the less dense conventional straw (although the U-value is higher due to t he smaller depth). The fact that th e k-values exceed the m inimum values is also to be expected as the wind speeds varied both above and below the 1 m/s at which the minimum would be expected.

Table 10. Heat losses from uncovered and straw-covered soil during a single night (18 to 19 November 2013) in Yorkshire when the air temperature dropped to -1.8°C.

Straw type	Depth (cm)	Density (kg/m^3)	Total heat loss (MJ/m^2)	Heat flux (W/m^2)	U-value (W/m^{2}K)	Effective k-value (W/mK)	Expected min. k-value (W/mK)
None	-	-	2.25	39.1	-	-	-
Rotary	10	12.7	0.72	12.5	3.12	0.31	>0.22
Conventional	20	26.2	0.49	8.5	2.07	0.42	>0.30

Potential alternatives

A wide range of tec hniques have been suggested. These are listed in the fol lowing table together with initial comments on their perceived merits/difficulties.

Table 11. List of potential options/alternatives that have been considered.

Option	Source	Notes/Comments	Take forward
Use less straw:			

Table 11. List of potential options/alternatives that have been considered.

Option	Source	Notes/Comments	Take forward
Improve straw recovery and reuse	BCGA	This is/can already be done. For successful storage the straw needs to be windrowed and dry, achieving this in the field may be difficult at the time of year that it needs to be done; requires additional passes with machinery in the field. Theoretically, U-values will be similar to fresh straw at same depth/density and moisture content, but greater t/ha may be needed to achieve the same initial depth as fresh straw.	?
Straw plus polythene over the top	VCS	This appears to be the cheapest option, with the most immediate payback in the short term. The key issues will be laying the polythene and keeping it in place, and whether a bottom layer of polythene is needed to keep straw as dry as possible	Yes
Sandwich straw between plastic between two layers of polythene	BCGA	See above. Main question is the practical value and benefit of having a bottom layer of polythene in relation to the extra costs.	Yes
Sticker to bulk up straw and retain depth through winter (sprayed at application through the spreader at rear of machine)	BCGA, VCS	This seems to be based on a mis-conception that a 'fluffed-up' layer will give more insulation. There seems to be no benefit compared to existing system.	No
Mix with a "swell gel" as used in some composts	BCGA	The increased water content will significantly increase thermal conductivity, reducing insulation value. No benefit.	No
Direct straw alternatives:			
		All straw alternatives based on plants or plant fibres, would have the potential to achieve similar U-values, if sufficient density and depth can be applied. However, they would also suffer from all the same limitations and inefficiencies as the current system, i.e. to achieve maximum insulation value they need to be kept dry.	
bean straw	BCGA	Likely to degrade more quickly if used as a direct replacement. But if available locally at lower cost than straw, could be useful for shorter term field storage.	?
rape straw	BCGA	Potential for increased risk of *Sclerotinia.*	No
miscanthus	BCGA Danes	Would need to be grown specifically for the purpose, therefore cost is likely to be high.	No
maize	Danes	The larger stalks are likely to create more open void space than wheat straw (Flerchinger *et al.* 2003), so will have comparatively lower insulation value for the same volume/tonnage; lower availability ?	No
Grass cuttings from non-cropped areas	Danes	Dry would have similar insulation value to straw; but likely to hold more moisture for a given depth if uncovered and will degrade quicker (depth reduced). Potential issues with weeds and insufficient volume. No benefit.	No
Hemp	Danes	Similar to all other fibres. Would have to be grown specifically, so higher cost.	No
Coconut fibre	Danes	Would need to be imported. Significant environmental footprint.	No

Table 11. List of potential options/alternatives that have been considered.

Option	Source	Notes/Comments	Take forward
Sphagnum	Danes	Environmental and sourcing issues.	No
Wood shavings	BCGA	Similar U-value to dense dry straw for a given depth; but would require 6x more t/ha than equivalent straw. Unknown impact of moisture if uncovered but likely to similar to or worse than straw. Residue would lock-up a lot of N.	?
Bark	Danes	Similar U-value to straw for a given depth; but requires ~10x more t/ha than equivalent straw. Unknown impact of moisture if uncovered but likely to similar to or worse than straw. Residue would lock up a lot of N. Could be economic if low cost local supplier, but the high t/ha would add to transport.	?
Shredded newspaper / other paper waste	BCGA	Excelfibre (http://www.excelfibre.com/), a 100% recycled product, would be feasible if between poly to keep dry. Similar biomass to equivalent straw depth under poly. Probably the cheapest non-re-usable, biodegradable, non-straw alternative.	Yes
PAS-100 Green waste + polythene.	PHS	Composted green-waste has a similar thermal conductivity to peat. If a supply is available locally, this could represent the lowest cost option. However, due to N content, the amount that can be applied is limited.	?
Use carrot canopy to help trap air by using sticker to prevent collapse and degradation. Perhaps with additional fungicide option to help maintain green-ness as long as possible.	BCGA VCS	This effectively already happens to some extent, and provides an additional layer beneath the straw layer or under the polythene.	No
Use canopy perhaps + additional green matter to provide heat source through composting	VCS, PHS	Difficult to control; preliminary calculations indicate that too much biomass would be needed, with high N, and moisture (so increasing heat loss) to generate sufficient heat long term. There could also be issues with the addition of non-composted waste in terms of either food safety or plant pathogen transfer.	No
Misting/sprinklers for frost protection. Also only considers half the problem – not the re-growth prevention in spring.	BCGA	Would only work for milder frosts; irrigation would be needed in all fields at same time; irrigation rates > 10 mm/h for several hours with monitoring through the night; will make wet soils wetter and increase run-off or leaching; does not deal with spring re-growth; not a 'fit and forget' option.	No
Fans to blow air for frost protection .	BCGA	Only effective for milder radiation frosts; fans would be needed in all fields on the same nights; energy cost; does not deal with spring re-growth; not a 'fit and forget' option.	No
Breeding:			
Frost tolerant or 'season extension' varieties in combination with reduced insulation.	BCGA	A key issue is market acceptance of any varieties. The 'frost-tolerance' needs to be quantified, it could be possible to calculate reduced straw requirements.	Yes

Table 11. List of potential options/alternatives that have been considered.

Option	Source	Notes/Comments	Take forward
Higher sugars / other solutes to increase resistance to freezing	VCS	This could be in effect what would be achieved in frost-tolerant varieties (see above). Also this is probably underlying mechanism of pre-conditioning.	?
Varieties with greater quantity of more robust, disease resistant and upright canopy to help protect crop?	BCGA	Basis is not clear? A more upright canopy would increase radiation loss from soil and trap less air.	No
Bolting resistant (limiting “woody” development)	BCGA	This will have benefits for later harvest dates, and with mild winters; unlikely to have any impact on straw requirements. For breeders to consider.	?
Grow further down into soil, pulling crowns away from surface	BCGA	See also frost tolerant varieties. The deeper the crown, the less susceptible to damage. Already there are differences between cultivars. Trials would be needed specifically to examine this and compare varieties in a standard way. Possibly combined with reduced straw.	Yes
Development of earlier varieties to bring the other end of the programme closer to late storage?	BCGA	There are inherent limitations on the rate of growth due to temperature, light levels and photo-period in the early part of the season, so the question is whether current varieties are already maximising. For breeders to consider.	?
Additional fungicide / nutrients (e.g. potassium) / plant health promoters/elicitors programme to try to preserve green foliage for as long as possible.	VCS	Most crops are already quite green when strawed, and the timing of current operations (and any likely alternatives) are driven by the logistics of getting all crops covered before the onset of cold weather.	No
Synthetic alternative insulation products			
All		Need to consider removal, transport and storage for all these, as well as potential for disease transfer.	
Bubble-wrap (silver/other opaque)	BCGA Danes	In themselves these would not provide sufficient insulation, but could be combined with reduced amount of straw, as an alternative top covering.	Yes
Multi-layer composite materials (multifoil/filler)	BCGA	These can provide more than sufficient U-values. More expensive than current. Would need to be re-used several times to be economic.	Yes
Simple polythene sandwich of a standard insulation material.	VCS	All of the 'wool' type materials (rock-wool, glasswool, natural wool, etc.) could provide enough insulation, provided they are kept dry in a polythene sandwich. More expensive than current so would need to be re-used several times to be economic.	Yes
Closed-cell polyethylene foam mat	VCS	A realistic alternative, although initially expensive, robust and could be re-used multi-times.	Yes
Pneumatic / inflated cover with no internal filler, perhaps just some structural support like an air-bed – could be deflated.	BCGA VCS	Continuous cost and maintenance of air blower, or high cost of leak proof material. Still air is a good insulator, moving air is not. Much more efficient to use trapped still air in more conventional insulation materials. No benefit compared to simpler alternatives.	No

Table 11. List of potential options/alternatives that have been considered.

Option	Source	Notes/Comments	Take forward
Water filled cover, perhaps with circulation to prevent freezing	BCGA	Water has high conductivity, but also high thermal mass if volume is large enough. Circulation in itself will not prevent freezing (seas and rivers still freeze), would need water/heat source (ground source heat or nearby water source). High cost of large area of thick material to avoid leaks. Maintenance issues. Difficult/costly to implement on the scale required.	No
Aerogel http://www.aerogel.com/	Danes	One of the best insulation materials in existence (better than air !). But very expensive, £21/m^{2}. Too expensive.	No
Cloches. Possibly + warm air blown through?	BCGA, Danes	Potential for machine installation; energy cost of warm air; may get too warm and encourage growth under mild conditions. No use for storage into spring. Won't deal with heaviest frost etc. Weight of snow could destroy. Conventional insulation materials are a better way of trapping the air.	No
Vattex capillary matting.	Danes	Feasible, but would need several layers and between polythene to match U-values of current straw, which then adds to the cost. Could be a useful alternative for short term storage. Would need second-hand supply or to re-use several times to be cost-effective.	Yes
Blown starch-type foam 'peanuts'	BCGA	The required level of insulation is achievable in a poly sandwich to trap air and keep dry; but need to be kept very dry to prevent degradation. Could be difficult/impossible to handle in windy conditions, creating a lot of nuisance value.	No?
Blown starch-type foam formed like a polyurethane foam for insulation – spread a few inches deep over whole crop to form a single solid foam layer that can then be chopped up in spring to decompose. Someone at BCGA suggested they had seen trials with this kind of system in Holland (or other N Europe) on cabbages.		Not found any details. Urea-formaldehyde foams (as apparently tested in work done by ADAS) are no longer used due to H&S issues. Possibly feasible if the foam was biodegradable in a controlled way, would probably also need to be covered with poly to prevent moisture ingress. Would be a whole research project alone to get it working.	?
Snow blowers operating in fields when frosty conditions present (using irrigation infrastructure).	BCGA Danes	Same problem as irrigation, or fans. All kit will be needed everywhere at same time. Probably couldn't cover enough area quickly enough without extortionate cost. Would need to be regularly replaced – snow mostly melts in the UK. Might be feasible in coldest locations.	No
Soil ridging:			
Alter growing configuration to 3 row system (in the centre of 2 m wheel centres) to allow sufficient free soil to make jumbo ridges to protect crop .	VCS Danes	This relies on the nature of the soil and its inherent thermal properties. Freezing of soil could prevent or make harvesting difficult. This would be most effective on dry peaty soils that are better insulators than sandy soils. Insulation efficiency would also be affected by soil moisture which cannot be controlled. Only for milder conditions.	?

Table 11. List of potential options/alternatives that have been considered.

Option	Source	Notes/Comments	Take forward
Ridging with additional straw to the top of carrots prior to ridging	VCS	Straw needs to be in layer trapping air. Effectively no different and no advantage compared to the current system.	No
Poly over the top of soil (either in single rows or as wide sheet 12m or 24m or similar).	VCS	If polythene is applied over the top, it would be most effective on dry peaty soils. It is probably more efficient to simply to poly over the top of a reduced thickness of straw.	?

Source (the originator of the idea):
BCGA – British Carrot Growers Association
Danes – Report from Denmark
VCS – Vegetable Consultancy Services

A comparison of the insulation value of the simplest straw-based alternatives is shown in Table 10. The starting point for the comparison is a 15.5 cm settled depth of dense straw at the moisture value as measured in the f ield. This comparison contains a n umber of assumptions that w ould need to be tested experimentally: in particular we assume that putting a layer of polythene over the top of the straw restores the effective conductivity of the straw layer to the equivalent of dry straw and eliminates the effects of forced convection (as wind cannot now penetrate into the straw layer). We also assume that a target depth of 5 cm is the minimum of straw that can be applied relatively uniformly. On this basis using only a third of the amount of straw (29 bales per ha), achieves a theoretical U-value in excess of that achievable with the current system. It must be emphasised that this is theoretical and would need to be c onfirmed experimentally. The m ain challenge would be to an chor the polythene and minimise any damage during the winter. Another consideration, particularly for crops stored into the spring, would be whether the polythene would need to be white or foil-coated to reduce heat gain, this would increase the cost of the polythene compared to the standard.

Table 12. Comparison of U-values for poly-over-straw vs. straw and straw-over-poly.

System	Bales per ha	Depth (cm)	Density (kg/m^3)	Moist. (%)	k-value (W/mK)	R_1	R_2	U-value (W/m^{2}K)	Material cost (£/m^2)
Dry straw	90	15.5	28.6	0	0.22	0.70		1.42	0.31
Dry + poly below	90	15.5	28.6	0	0.22	0.70	0.15	1.17	0.36
Moist straw	90	15.5	28.6	286	0.31	0.51		1.97	0.31
Moist + poly below	90	15.5	28.6	286	0.31	0.51	0.15	1.52	0.36
Poly top + straw	29	5	28.6	0	0.065	0.77	0.15	1.09	0.15
Foil + straw	29	5	28.6	0	0.065	0.77	0.34	0.90	?

Evaluation of selected non-straw alternatives

A selection of the U-values and costs of some of the most feasible, non-straw alternatives is shown in Table 11. The costs provided are for the costs of the materials and do not include the costs of laying and storage if re-used. In some cases it is likely that the costs would be reduced with bulk orders and depending on proximity to the suppliers. The majority of these alternatives are more expensive compared to the current system and so would only be feasible if the material could be re-used several times, or if the price of straw increased further. Descriptions of these options follows.

Multifoil quilts

These are commonly used in the building industry for wall and particularly roof insulation and consist of several layers of reflective foil separated by thin layers of a 'wool' type insulation material. They can provide more than adequate insulation value, and possibly cheaper versions with lower insulation values could be produced if there was sufficient demand. Even so, they would need to be re-used several times to be cost-effective, and anchoring and robustness would be an issue. Possibly using widths that cover multiple beds, and anchoring manually would be the best way to make effective use.

Rockwool

Standard rockwool types of roof insulation, at a thickness of 5 cm would provide more than adequate insulation value if sandwiched between polythene to keep it dry. It would need to be re-used several times to be effective, and although anchoring would be an issue, we envisage it would be similar to dealing with poly over straw. It would need to be stored dry for re-use. Reduced thicknesses of 2 or 3 cm would provide adequate insulation (but appear not to be available), although this would mean that the effective life of the standard thickness material could be prolonged.

Vattex

Vattex capillary matting is widely available in horticulture. To be effective, it would need to be kept dry by sandwiching between two layers of polythene. A single layer of matting would not provide sufficient insulation for all except the earliest harvested crops. A double layer just about matches moist straw, but would obviously double the cost of material. It would need to be re-used several times to cost-effective. It there was a local source of second-hand material it might become more cost-effective.

Green Waste

A thick layer of green waste with a polythene cover or in a polythene sandwich, could provide sufficient insulation, and would be cheaper than straw if there is a relatively local supply. However, the nitrogen content would mean that the amounts required would exceed nitrogen application limits.

Starch peanuts

Blown starch peanuts as often used in packaging, in a polythene sandwich, would provide adequate insulation, and would be highly biodegradable. They would be very sensitive to moisture ingress, re-use would be difficult, and would potentially have a lot of nuisance value in windy conditions. Given the cost this does not seem a feasible option.

Bark, wood shavings

Both bark and wood shavings, if dry, would have a similar insulation value to the same depth of dense dry straw. Thus adequate insulation could be achieved with a 5 cm depth covered with polythene. Particularly for wood shavings, if there was a local supplier costs could be brought down, but the weight needed to achieve the same depth as the equivalent amount of straw (at least double) would mean that nitrogen lock-up for subsequent crops could be a significant issue, and certainly worse than the current straw systems.

Excel fibre

We originally investigated Warmcel loft insulation, but the manufacturer recommended Excelfibre as a cheaper alternative. In a polythene sandwich, a 5 cm depth would provide more than adequate insulation. This is probably the cheapest feasible non-straw alternative, and the weight required is similar to the same depth of straw, so issues with N-lock up would be less than the current straw system.

Closed-cell PE foam

Most of the insulation materials need to kept dry for effective insulation, and so would need to be sandwiched between two layers of polythene, so as with polythene on top of straw, anchoring the polythene and ensuring its integrity throughout the winter present a challenge. The exception to this, is closed-cell polyethylene (PE) foam, this is the same material as used in sleeping mats, and is also used in the building industry for frost protection of freshly laid concrete. Due to the closed-cell structure, the insulation value of the material is unaffected by moisture. It is probably also one of the most robust options examined, with potential for considerable re-use. In addition it could be washed or disinfected to prevent disease transfer, and could be stored outside. Possibly it could be used in combination with straw, e.g. to supplement straw for longer-terms crops. The main challenge would be anchoring in the field: possibly using multi-bed widths and manual anchoring, or with reduced straw as a direct replacement for polythene underneath. If used in multi-bed widths, perforations could be added to allow drainage at wheelings.

Table 13. Calculated U-values and material costs for selected alternative field storage options

System	t/ha	Density (kg/m^3)	Depth (cm)	kg/m^2	k-value (W/mK)	R_1	R_2	R_{si}	R_{se}	U-value (W/m^2)	£/m^2	Notes
Moist straw (90 bales/ha)	45	28.6	15.5	4.43	0.31	0.51	-			1.97	0.31	Current system
SF19 (multifoil)	6.9	-	3.8	0.69		2.21	-	0.11	0.033	0.42	5.00	Exceeds insulation needs.
TLX Gold (breathable)	9	-	3.3	0.90		0.95	-	0.11	0.033	0.91	1.50	Price indication from manufacture.
Poly + Rockwool + poly	5	10	5	0.50	0.044	1.14	0.15	0.11	0.033	0.70	2.00	
Poly + 2 layers Vattex + poly	7.5	94	0.8	0.75	0.037	0.22	0.15	0.11	0.033	1.96	2.40	
Poly + 1 layer Vattex + poly	3.8	94	0.4	0.38	0.037	0.11	0.15	0.11	0.033	2.49	1.20	
Closed PE foam	2.6	35	0.75	0.26	0.037	0.20	-	0.11	0.033	2.89	1.46	Most easily re-used, with longest life.
Closed PE foam	7.0	35	2	0.70	0.037	0.54	-	0.11	0.033	1.46	3.68	
Poly + Excel fibre + poly	17.5	35	5	1.75	0.044	1.14	0.15	0.11	0.033	0.70	0.80	Cheapest realistic alternative.
Poly + PAS100 GW + poly	200	400	5	20.0	0.060	0.83	0.15	-	-	1.02	0.07	This amount of green-waste would exceed N limits
Poly + starch peanuts + poly	3.25	6.5	5	0.325	0.040	1.25	0.15	0.11	0.033	0.65	1.72	Difficult to handle
Poly + wood shavings + poly	80	160	5	8.0	0.065	0.77	0.15	0.11	0.033	0.94	0.72	Issues with N-lock up
Poly + Bark	107	213	5	10.7	0.060	0.83	0.15	0.11	0.033	0.89	1.10	Issues with N-lock up
Foil/Bubble		-	0.4	-	n/a	0.12	-	0.11	0.033	3.75	1.49	
Poly alone		-	-	-	n/a	-	0.15	-	-	6.67	0.05	

Discussion

In situ field storage under a layer of straw with or without a layer of polythene underneath is the primary means of storage for UK carrot crops marketed in the winter and spring. The base temperature for carrot growth is around 1°C, suggesting that the ideal storage temperature is in the range 0-2°C.

The literature on mass heat (energy) transfer in the soil, in insulation layers, and between the soil surface and atmosphere has been investigated. The temperature of the soil surface is dependent on the rate of heat/loss or gain from the surface to the atmosphere and the rate of heat transport up and down the soil profile. The deeper layers of the soil act as a reservoir of heat energy. Adding a layer of straw to the surface acts as an insulation layer reducing heat loss during colder periods in the winter and reducing heat gain in the spring. The principles are well understood for the soil/air systems and there is a lot of information on the theory of insulation from the fields of building and engineering. The insulation properties of materials are usually characterised using one or more of the following terms: the k-value, the R-value and the U-value. Good insulators have a low k- and U-values and high R-values.

Characterising the current system is complicated due to the dynamic and thermodynamically unstable nature of the system. Most studies of the insulative properties of materials have been done in the context of building and engineering, with measurements done under thermodynamically stable conditions. There have been some studies and modelling of the effects of 'mulches' on soil temperature and moisture content, but many of these have been in the context of moisture conservation in arid and semi-arid conditions.

There are three main aspects of the current system that have significant impact on the efficiency of the straw layer as insulation: straw density, forced convection (as a result of wind penetration), moisture content.

Density: as the density of the straw layer decreases, the effective k-value (conductivity) increases, so the insulation value decreases. This means that having a light fluffy layer of straw is less effective as insulation than the same depth of dense straw.

Forced convection: as the straw layer is not sealed, moving air can penetrate into the surface layers, this air movement increases heat loss, and so the effective k-value increases with increasing wind speed and the insulation value decreases.

Moisture: the presence of moisture in the straw increases the effective k-value and decreased the insulation value. This results from the higher conductivity of water and from the movement of water vapour. Moisture contents of up to 286% were measured in straw samples from field crops. Given that in the UK straw is likely to remain relatively wet throughout most of the winter, the overall insulation value of the straw layer is considerably reduced.

Using soil temperature data logged at hourly intervals and every 10 cm in the top 40 cm depth of soil under three different surface coverings, we were able to estimate the amount of heat lost from the soil surface on one of the coldest nights (minimum air temp -1.8°C). The total net heat lost from uncovered soil was around 2.25 MJ/m^2 or 39 W/m^2, compared to 3.1 and 2.1 W/m^2 under 10 cm of dense straw and 20 cm of less dense straw. The resulting estimates of the thermal conductivity (k-values) of the straw layers were consistent with those predicted from values in the literature for straw mulches with forced convection.

The role of the polythene layer in the current system is not clear cut. Growers perceive that light-exclusion is important for longer-term storage and discount the insulation value it provides. Apparently the use of polythene came about as a result of previous ADAS work (J. Birkenshaw, 2014, pers. comm.). There appears to be no information on the effects of light on carrot re-growth, which seems to be mainly temperature dependent and calculations indicate that insulation value of the polythene sheet may be equivalent to 3 to 5 cm depth of straw. Thus it may be that the improved storability achieved with a polythene may be due to the greater insulation value of the system as a whole rather than light-exclusion.

Another factor reducing the overall insulation value is the effect of the wheelings. When grown on a conventional bed system, wheelings account for approx. 16% of the area. Wheelings are not actively covered with straw, so the incidental covering with straw is thinner. If we estimate that the depth of straw in the wheelings is about half that on the beds, this means that the rate of heat loss will be double for 16% of the area. This thermal bridging effect increases the potential overall heat loss for a field compared to spreading the same amount of straw evenly over the whole area. The resulting surface undulations may also create localised 'frost-pockets'.

Using less straw

Theoretical calculations suggest that making more efficient use of straw by keeping it dry and eliminating forced convection would have a major impact on the amount of straw required. This could be achieved by covering the top of the straw layer with a layer of polythene. Results indicate that a 5 cm layer of straw covered with polythene would provide the equivalent insulation to 28 cm of uncovered, wet straw, or 20 cm of uncovered, dry straw. Thus it would seem that potential savings in the amount of straw used of up to 75% could be achieved by covering the straw with a layer of polythene. It should be noted that these are theoretical calculations, so it is vital that they are tested experimentally, before wide scale adoption in practice. A further benefit of using less straw would be less N lock-up for subsequent crops. Other aspects that would also need to be examined experimentally are:

(i) whether there would be a need for, or the relative importance of also having a layer of polythene beneath the straw to minimise moisture levels in the straw;

(ii) the influence of the emissivity (reflectivity) of the covering layer, particularly for longer-term storage into the spring, i.e. does the cover need to be white or reflective to minimise heat gain in the spring?

It is likely that there would be two main challenges to a poly-over-straw system compared to the current system: (a) anchoring the polythene in place (b) avoiding physical damage/breeches in the polythene that would reduce the insulation value of the covering. There are perhaps a number of approaches to (a):

(i) Apply a second layer of straw over the top of the polythene, this would mean that reduction in the amount of straw used would be lower, but even if the overall amount of straw used was only reduced by a third, this would still achieve potential savings of around £1000 per ha. It is likely that this approach would also deal with (b) by providing direct protection and an insurance layer.

(ii) Cut the polythene into the soil at the time of laying as used in current plastic mulch/film covering equipment.

(iii) Specifically apply an additional thick layer of straw to the wheelings to cover the polythene edges.

(iv) Apply the polythene cover across multiple beds with manual anchoring at the edges.

In addition to dealing with (b) by (i) above, there may be a need to use thicker polythene than the 40 µm commonly used at present. This would of course increase costs. Alternatively, provided it is relatively not too great, some loss could be allowed for by increasing the straw depth.

Apparently, previous ADAS work also indicated that using poly-over-straw reduced straw use by 50%, but was not taken up by growers due to damage to the polythene by wild life and slower application rates. A similar result was obtained with a straw-poly-straw, but with less damage to the polythene (J Birkenshaw, 2014, pers. comm.)

Currently the timing of straw application to crops is driven by the logistics of getting the area covered before the onset of cold weather. Suggestions in the literature, that pre-conditioning at low temperatures may increase cold tolerance, mean that many crops are covered too early to take advantage of this, and so require more straw than would otherwise be the case.

Given the potential savings that can be made in the amount of straw used, it seems that these are likely to more than offset any additional costs of laying and polythene disposal Reduced amounts of straw could also be combined with other systems, e.g. frost-tolerant varieties with deeper crowns, delaying covering, but experimental data would be needed to quantify the relative impacts of system components.

Alternative insulation materials

A wide range of alternative materials have the potential to achieve equivalent insulation values to straw, especially if they can be kept dry.

Plant-based, straw or straw-like materials are likely to have similar insulative properties to straw if they can be applied at sufficient depth and sufficient bulk density. However, in most cases they are unlikely to be more efficient than straw, in terms of either volume or biomass required per ha. Also, they would all have the same issues with moisture and forced convection, and N lock-up for subsequent crops. Nevertheless if alternative fibrous materials can be obtained locally at low cost, they may be worth investigating as to the amounts needed to achieve sufficient depth and density to replace straw.

At present, most of the non-straw alternatives are likely to be more expensive than straw, so only become feasible if they can be re-used several times or if the price of straw increases further. It should also be considered that costs of some materials could come down if purchased in the bulk quantities that would be required for carrot field storage. Nevertheless some of these non-straw alternatives would still be worth investigating to have on hand as back-up or additional or supplementary options in case of problems with straw availability.

The cheapest non-straw alternative examined was a layer of PAS100 composted green-waste sandwiched between polythene. However the amount required (up 200 t/ha) would preclude its use due to nitrogen application limits. Bark or wood-shavings sandwiched between polythene are also amongst the cheapest alternatives considered, but the amount required to achieve adequate depth (80 to 100 t/ha) would have much greater impact on N lock-up than straw. Possibly the two effects could be combined, e.g. a mix of green-waste and wood-shavings would counteract each other and effectively provide long-term slow release of N into the soil. However, the dynamics of N release and availability in such a system would likely need further study to ensure there were no detrimental cropping and environmental impacts.

Although relatively expensive initially, closed-cell PE (polyethylene) foam, is worthy of further consideration. This is the material typically used in outdoor sleeping mats and as frost protection for freshly laid concrete. It has the major advantage that, unlike most other materials (including straw), it's insulative properties are unaffected by moisture. It is also robust and would have the potential to be re-used for several years, and would not require covered storage. We envisage that this could be most readily used in the short-term as a replacement for the polythene layer under a reduced straw layer for later crops. A key factor for its widespread uptake would be the number of times it can be re-used. The cost of re-cycling or disposal would also need to be considered in relation to the number of times that it could be re-used.

Excelfibre (http://www.excelfibre.com/) in a polythene sandwich is another alternative that could become feasible as a single-use option if straw costs increase. This is an industrial 100% re-cycled cellulose-fibre type product similar to one that has been developed as loft insulation (Warmcel) and with similar insulation properties. Discussions with the company indicated that they would be receptive to developing a system.

We aware that some previous work was done by ADAS, and a there has been a Defra/ADAS publication (Carrot storage: a guide to crop management for in-field storage and the disposal of straw and plastic). However we have been unable to obtain a copy of the publication from Defra (even though it is listed on their database) or access details of the results from the ADAS work.

Conclusions

The insulation properties of straw are affected by bulk density, moisture content, and forced convection.

The current carrot field storage systems of straw or straw-over-poly make inefficient use of the potential insulation value of straw.

Spreading the same amount of straw evenly across the entire field (including wheelings) is likely to be more efficient than just applying to beds and could educe overall heat loss by around 6%.

The insulation value of the polythene in straw-over-poly is not negligible, but its value for light exclusion has not been established. This needs to be investigated.

In the short-term, significant reductions in straw use (possibly up to 75%) can <u>theoretically</u> be made by covering the straw with polythene to keep it dry and prevent forced convection. This needs to be confirmed experimentally.

A range of potential alternatives to straw have potential to provide equivalent or better levels of insulation than the current system.

The current material costs for most non-straw alternatives are higher than the current cost of straw and only become cost-effective if they can be re-used or if straw prices increase significantly.

At least two non-straw alternatives are worth practical experimental investigation: closed-cell PE foam and Excelfibre in a polythene sandwich. Respectively, these are highly re-usable and at the lower end of the cost scale.

Closed-cell PE foam could be used as a supplement in the current system if straw is in short supply.

Some non-straw alternatives could possibly be combined to improve their feasibility.

Growers should consider funding experimental work to (a) validate the theoretical calculations reported here; (b) to confirm the potential of the most feasible alternatives so the information is readily available in case of straw price increases or supply issues; (c) understand the effects of light and light-exclusion on spring re-growth and quality; (d) evaluate the effect of pre-conditioning (pre-chilling) prior to covering; (e) develop a model that can be used to accurately predict insulation/straw requirement for different situations.

Knowledge and Technology Transfer

Presentation to BCGA 16-Jan-2014.

Presentation to BCGA technical day on 20th March at PGRO.

Selected References

Arya, P.S. (2001) *Introduction to Micrometeorology*. Academic Press.

Benjamin, L.R. & Aikman, D.P. (1995) Predicting Growth in Stands of Mixed Species from that in Individual Species. *Annals of Botany*, **76**, 31–42.

Brewster, J.L. & Sutherland, R.A. (1993) The rapid determination in controlled environments of parameters for predicting seedling growth rates in natural conditions. *Annals of Applied Biology*, **122**, 123–133.

Bussière, F. & Cellier, P. (1994) Modification of the soil temperature and water content regimes by a crop residue mulch: experiment and modelling. *Agricultural and Forest Meteorology*, **68**, 1–28.

Van Donk, S. & Tollner, E. (2000a) Measurement and modelling of heat transfer mechanisms in mulch materials. *Transactions of the ASAE*, **43**, 919–925.

Van Donk, S. & Tollner, E. (2000b) Apparent thermal conductivity of mulch materials exposed to forced convection. *Transactions of the ASAE*, **43**, 1117–1127.

Flerchinger, G.N., Sauer, T.J. & Aiken, R.A. (2003) Effects of crop residue cover and architecture on heat and water transfer at the soil surface. *Geoderma*, **116**, 217–233.

Gómez Galindo, F., Elias, L., Gekas, V., Herppich, W.B., Smallwood, M., Sommarin, M., Worrall, D. & Sjöholm, I. (2005) On the induction of cold acclimation in carrots (Daucus carota L.) and its influence on storage performance. *Food Research International*, **38**, 29–36.

Paulsen, O. (2010) *Winter cover for carrots - thermal engineering assessment of options (translated from Danish)*. Center for Energieffektivisering og Ventilation.

Riha, S.J., McInnes, K.J., Childs, S.W. & Campbell, G.S. (1980) A Finite Element Calculation for Determining Thermal Conductivity. *Soil Science Society of America Journal*, **44**, 1323.

Snyder, R.L. & Paw U, K.T. (2000) Soil Heat Flow and Temperature. URL http://biomet.ucdavis.edu/biomet/SoilHeatFlow/SoilHF.htm [accessed 3 January 2014]

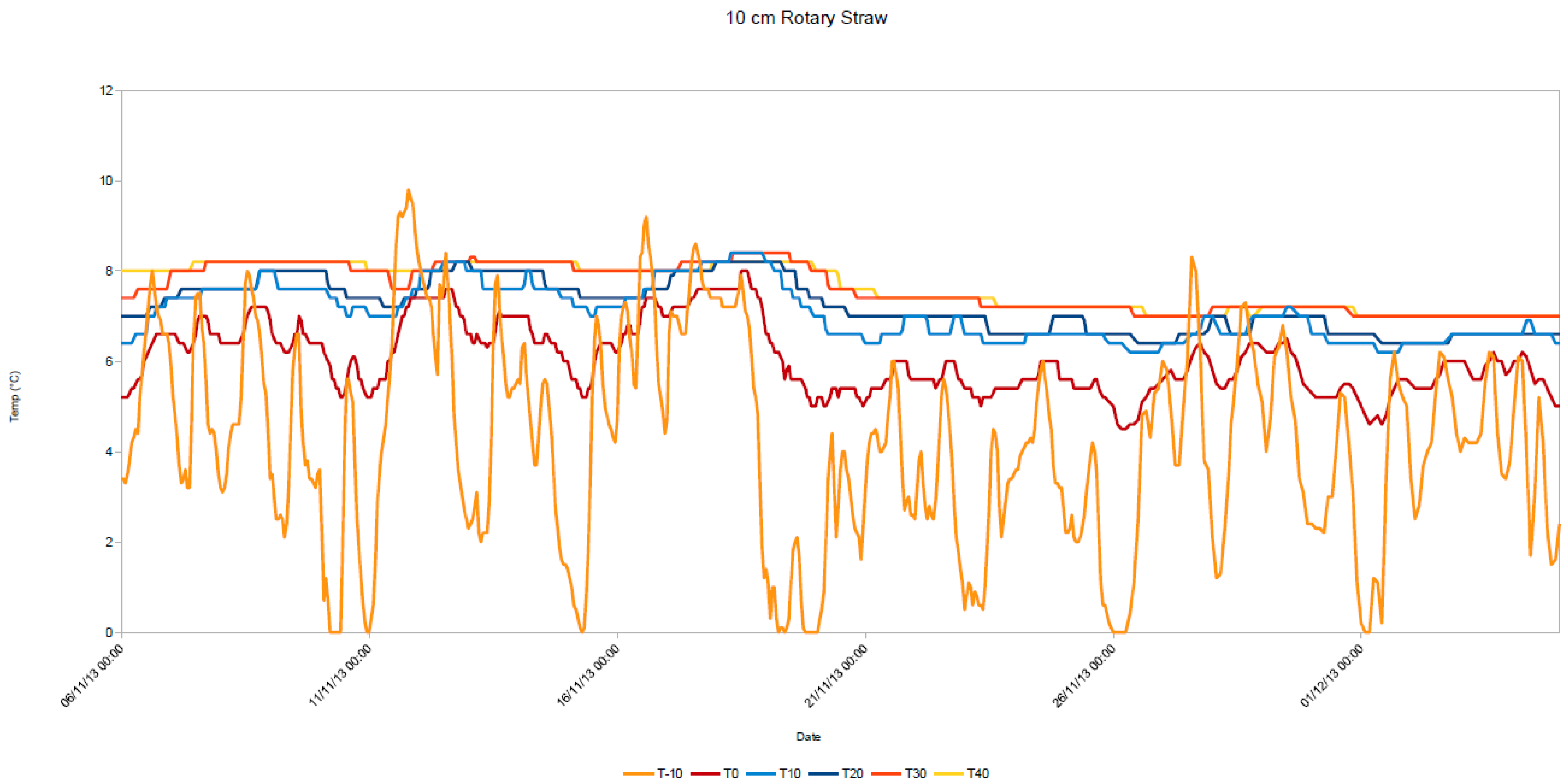
Suojala, Tehri. (2000) *Pre- and Postharvest Development of Carrot Yield and Quality*. University of Helsinki, Helsinki.

Suslow, T.V., Mitchell, J. & Cantwell, M. Carrot: Recommendations for Maintaining Postharvest Quality. URL http://postharvest.ucdavis.edu/pfvegetable/Carrots [accessed 3 December 2013]

De Vries, D.E. & Afgan, N.H. (1975) *Heat and Mass Transfer in the Biosphere*. John Wiley & Sons, Cichester, UK.

Appendices

Graphs showing the soil temperature at different depths under different coverings in the same field.



10 cm Rotary Straw
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8
6
4
2
0
Temp (°C)
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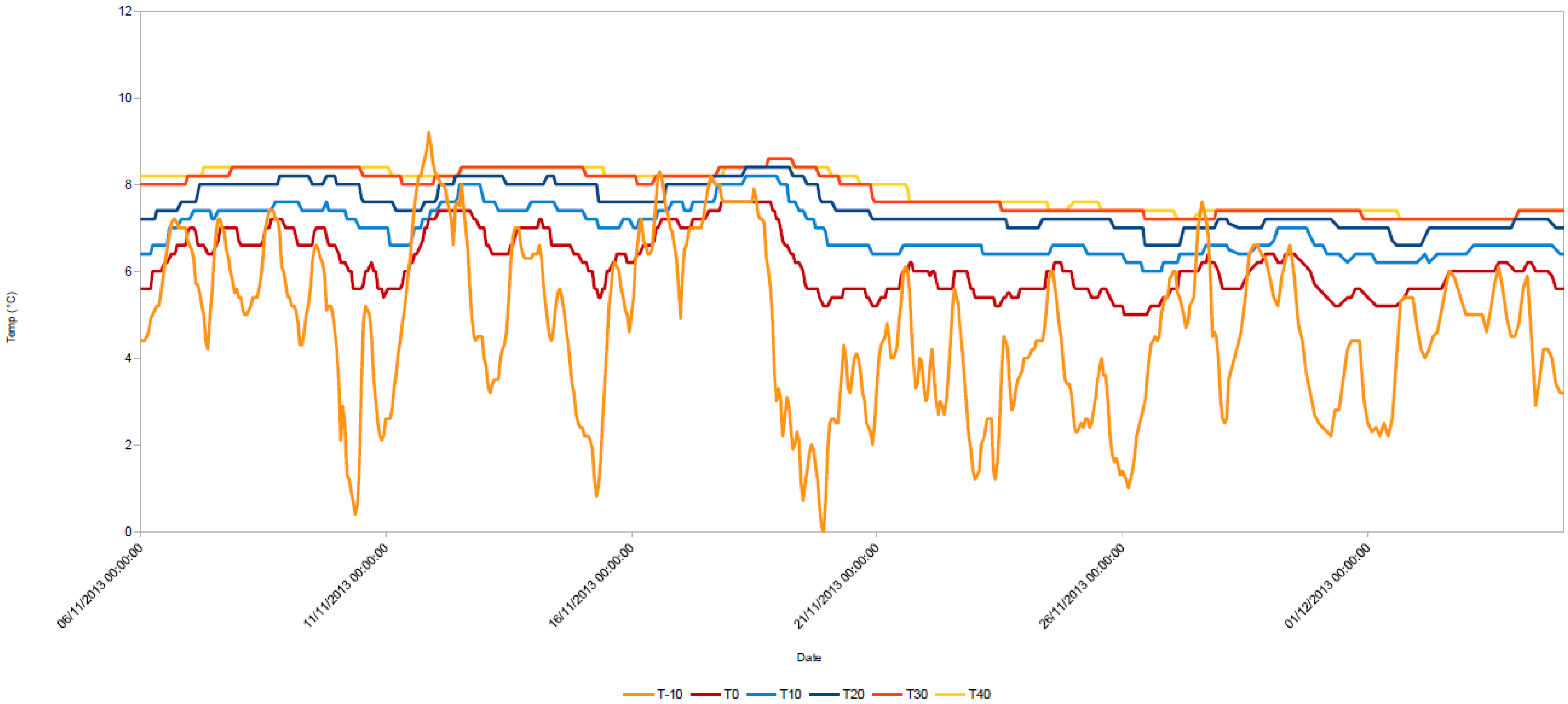
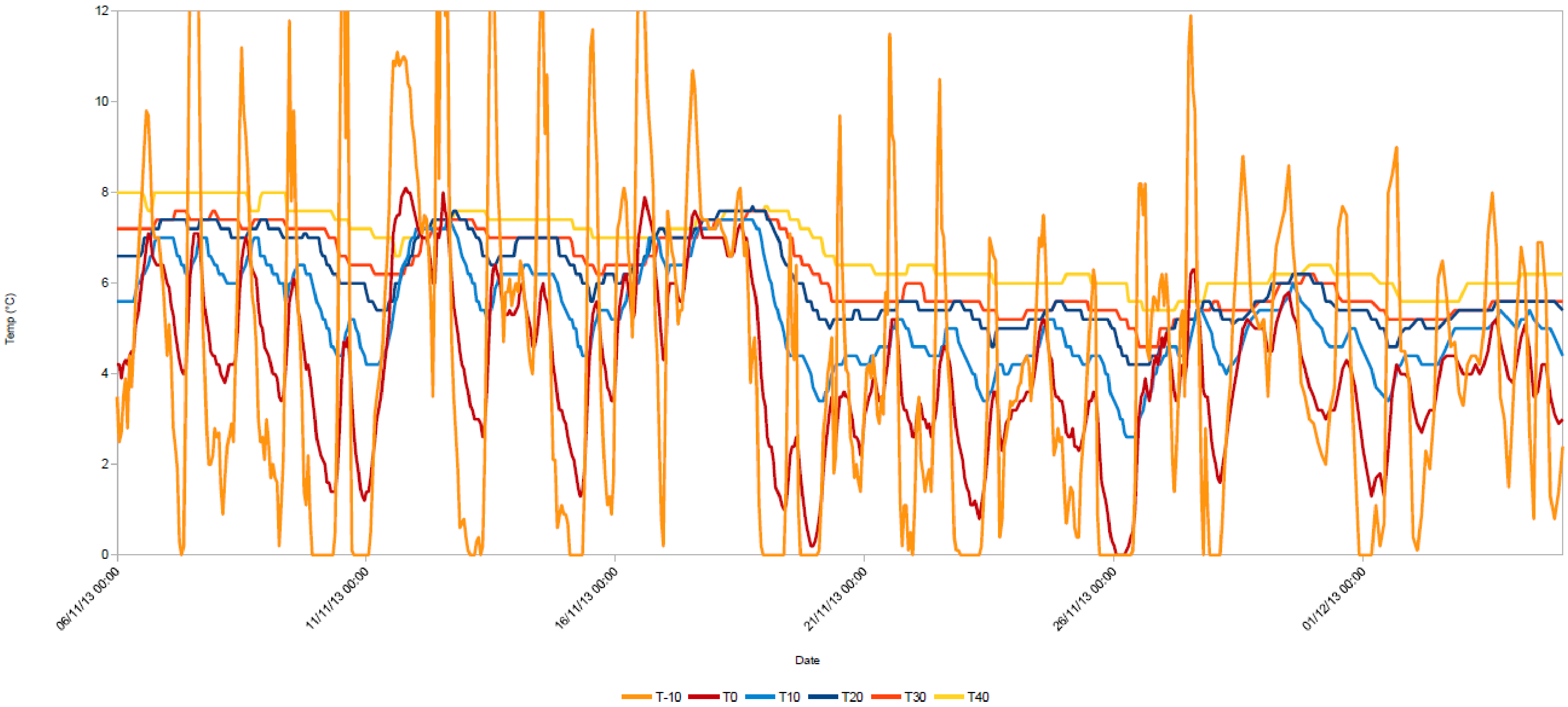
11/11/13 00:00
16/11/13 00:00
21/11/13 00:00
26/11/13 00:00
01/12/13 00:00
Date
T-10
T0
T10
T20
T30
T40

20 cm Conventional Straw



Uncovered



Temp (°C)
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6
4
2
0
06/11/13 00:00
11/11/13 00:00
16/11/13 00:00
21/11/13 00:00
26/11/13 00:00
01/12/13 00:00
Date
T-10
T0
T10
T20
T30
T40

