Project title:	Practical evaluation of carrot field storage alternatives
Project number:	FV 398b
Project leader:	Dr S J Roberts, Plant Health Solutions Ltd
Report:	Final Report, Nov 2017
Previous report:	Annual report, Dec 2016
Key staff:	Dr S J Roberts (PHS) James Howell (VCS)
Location of project:	VCS, Wellbeck; PHS, Warwick; Trial sites in Norfolk, Aberdeenshire, Yorkshire.
Industry Representative:	Mr Rodger Hobson, Hobson Farming, YO19 4SR
Date project commenced:	01 Aug 2015
Date project completion due:	30 Sep 2017

DISCLAIMER

The results and conclusions in this report are based on an 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
Director
Plant Health Solutions Ltd.

Signature .... Date ....

Report authorised by:
Dr S J Roberts
Director
Plant Health Solutions Ltd.

Signature .... Date ....

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GROWER SUMMARY

Headline

- All of the reduced-straw and non-straw alternatives provided adequate frost protection for field-stored carrot crops during the winters of 2015-16 and 2016-17.
- Cellulose fibre or similar materials could be a realistic alternative to conventional straw if suitable prices can be negotiated.

Background

Current 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 an additional layer of polythene below) to provide insulation against frost damage during the winter and to prevent warming and re-growth in the spring. However, field storage using straw is becoming increasingly problematical and challenging as a sustainable technique. This is 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, and the potential for introduction of problem weed seeds with the straw. Supplies of straw are likely to become both more expensive and erratic in future years due to 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. In addition, landowners have a major concern that importing straw may introduce blackgrass seeds into fields which have been previously free. Although not considered a severe problem on sandy (carrot) soils, there is a fear that once present on a farm it could move on to other fields with heavier soil.

There is therefore a demand to examine alternative options for in-field storage of carrots which do not rely on the use of large quantities of straw: either through reduced quantities of straw or non-straw alternatives. A previous project, FV 398a, (Roberts & Lacey, 2014) primarily a theoretical desk-based study, investigated:

- heat transfer principles involved in field storage
- the theoretical insulation value of current methods
- the cost and issues involved in using alternative insulation materials

The project identified inefficiencies (in terms of insulative value) in the current straw-based systems, some possible misconceptions, and alternative systems and materials that could have equivalent or better insulative value to the current system. However, estimates of insulative value of alternative systems were theoretical.

This project aims to:

a) Validate the theoretical insulative values for alternative materials and their impact on crop quality; and

b) Investigate practical implementation of alternative systems.

This final report summarises the results of both years of the project (2015-16 and 2016-17).

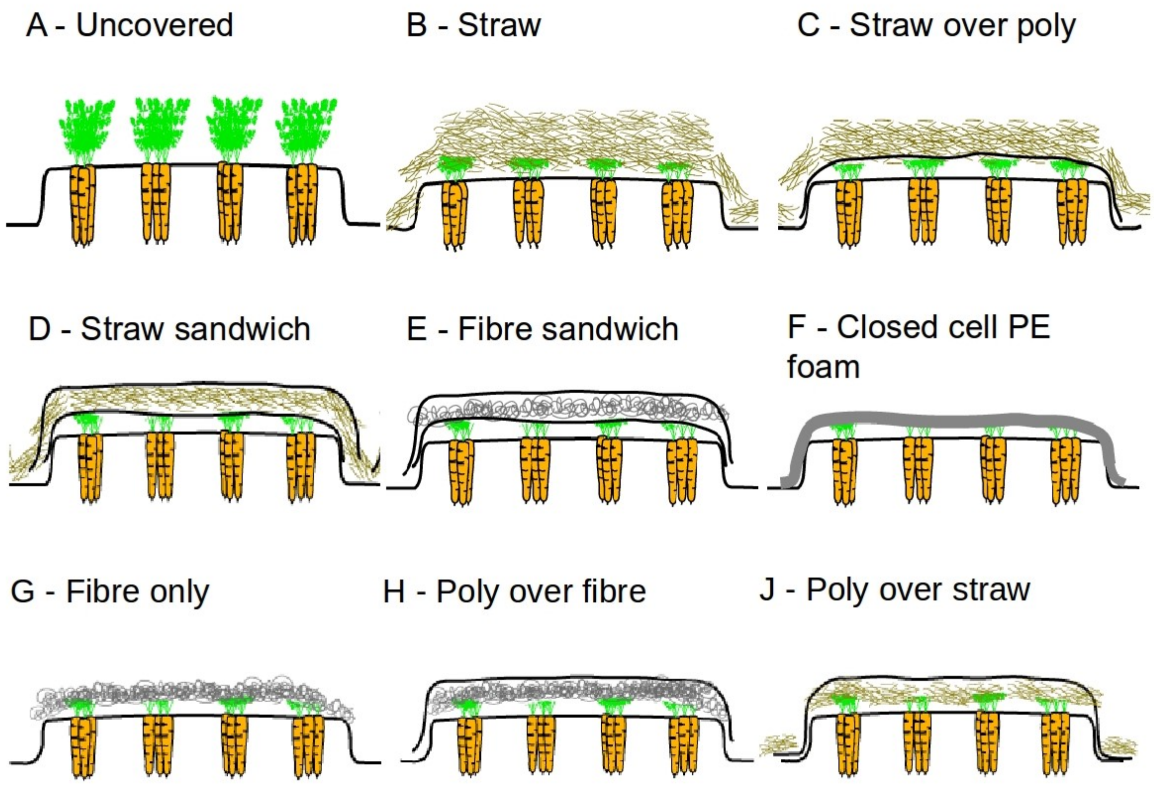
Summary

Field trials were established in commercial strawed crops of cv. Nairobi. Six treatments (untreated control plus five others) (Table 1, Figure 1) were examined at three different locations (Norfolk, Scotland and Yorkshire) and with two harvest dates over two winters (2015-16 and 2016-17). Each plot was 6 to 8-beds wide by 10 m long. Soil temperature and moisture sensors were inserted into each plot at depths of up to 50 cm and relayed hourly data records via the mobile-phone network.

Table 1. Treatment codes and details.

Year	Code	Treatment	Details/Notes
1 & 2	A	Uncovered control	Untreated control.
1 & 2	B	Straw alone	Standard covering of straw (commercial standard). All sites in year 1, one site in year 2.
1 & 2	C	Straw over polythene	Straw with a single layer of black polythene below (commercial standard). All sites in year 1, two sites in year 2.
1	D	Reduced straw polythene sandwich	Reduced (~1.5kg/m^2) amount of straw with layer of black polythene below and layer of black polythene over the top. Year 1 only, modified for year 2 → J.
1	E	Cellulose fibre polythene sandwich	Cellulose fibre, approx. 5 cm depth, 1.75 kg/m^2 with a layer of black polythene below and a layer of white polythene over the top. Year 1 only, modified for year 2 → H.
1 & 2	F	Closed cell PE Foam	Natural/white coloured, closed cell polyethylene foam, 7.5 mm thick, with a layer of white polythene over the top to provide anchorage. All sites in both years, material stored and re-used in year 2.
2	G	Cellulose fibre	Cellulose fibre, approx. 5 cm depth, 1.75 kg/m^2. Blown onto beds. Year 2 only.
2	H	Cellulose fibre with polythene cover	Cellulose fibre, approx. 5 cm depth, 1.75 kg/m^2. Blown onto beds, then covered with black polythene. Year 2 only.
2	J	Reduced straw with polythene cover	Reduced (~1.5 kg/m^2) amount of straw covered with black polythene, plus straw in wheelings to anchor. Year 2 only.

Figure 1. Diagram demonstrating each of the treatments



All of the treatments provided effective frost protection during both winters. The only significant frost damage occurred in the uncovered control (A). Based on experience in 2015-16, some of the treatments were modified for 2016-17 to make them more practical for application on a commercial field scale. For brevity only results for the second year are presented in the grower summary. The levels of total damage in 2016-17 (frost-damage and crown-rots) are shown in in Figure 2. The average U-values (measures of insulation value) are shown in in Figure 3 for 2016-17 for both heat loss and heat gain by the soil.Descriptions and comments on each of the treatments examined in 2016-17 are given below:

Descriptions and comments on each of the treatments examined in 2016-17 are given below:

Uncovered (Treatment A)

This treatment was included as a negative control in both years and at all sites. Inevitably the harvested carrots had significant levels of frost damage, and reduced marketable yields compared to the covered plots.

It would be expected that levels of frost damage would be correlated with how cold each site was, and this was the case in 2015-16 where the most severe damage occurred at the coldest site (Aberdeenshire). In 2016-17, this was not the case; the coldest site was again

Aberdeenshire, but there was no frost damage at the first harvest (end of January) and damage was still at a relatively low level at the second harvest, with the most severe frost damage seen at the Yorkshire site. The most likely reason for the difference was that at the Scottish site, the crowns were not exposed and were generally at or below the soil line, whereas at the Yorkshire site (with large roots destined for processing) crowns were exposed and often 1 cm above the soil line. In addition, (although not measured) it was perceived that there was a greater mass of foliage at the Scottish site, which could in itself reduce the rate of heat loss from the soil surface. This suggests that simply ensuring that crowns are covered with soil (e.g. by choice of variety or by cultivating between rows to ensure they are covered) could eliminate the need for, or reduce, the amount of straw required for earlier harvested crops.

Straw alone (Treatment B)

This treatment was included as a positive control and commercial standard, and to obtain baseline data for current practice. It was included at all sites in 2015-16 and at one site in 2016-17. Growers tend to use straw alone for shorter term crops, or when the crop may be processed and some damage to crowns is acceptable. This treatment provided slightly less insulation than straw over polythene (treatment C). The straw remains wet at the bottom (but not as wet as treatment C), and based on moisture contents at the final harvest the water content was equivalent to up to 8 kg/m^2. This has two effects: providing a thermal mass effect (dampening of temperature fluctuations, and the water in the straw will freeze before the soil/crop) and evaporative cooling. It is likely that both the thermal mass effect and the protection resulting from release of latent heat when water in this layer freezes is an important aspect of the protection provided. In 2015-16, the soil in the beds was wetter in this treatment than the others which all had a covering of polythene, but this was not the case in 2016-17.

Straw over poly (Treatment C)

This treatment was included as a positive control and a commercial standard, to obtain baseline data for current practice and to understand more about the role and benefits or otherwise of the polythene layer. It was included at all sites in 2015-16 and at two sites in 2016-17. Growers planning long-term field storage of crops generally use straw-over-poly system. The introduction of a polythene layer provides additional insulation through surface resistance to heat transfer, and so overall provides slightly greater insulation than straw alone (treatment B). However, the most important effect of the polythene was that the straw remains much wetter than straw alone (up to twice the moisture content), and often with free water on the surface of the polythene. Based on moisture contents of the straw at the final harvests the water content was equivalent to as much as 14 kg/m^2. This larger amount of water provides a greater thermal mass and greater potential for evaporative cooling. Thus, not only does this mean that the crop is more protected from freezing, but also heats up less slowly in the spring (i.e. is kept thin a narrower temperature range than the other treatments). Hence treatment C appeared to be the most effective insulation against incoming heat.

In the previous project (FV 398a) growers often reported that the main benefit of the polythene under straw was light-exclusion to prevent re-growth. There is no evidence for this. We conclude that the beneficial effect of the polythene perceived by growers is primarily a result of the greater thermal mass, and evaporative cooling effects, which in turn maintain soil and carrots at a lower temperature in the spring.

Poly over reduced straw (Treatment J)

This treatment was examined in the second year only, and was a modification of the reduced-straw polythene sandwich of the first year, simplified by omission of the polythene layer below the straw and using a minimal amount of straw in the wheelings to anchor the polythene.

The omission of the lower layer of polythene made little difference to the insulation values whilst reducing costs and making it more practical for field scale deployment. Whereas in the first year the top layer of polythene was anchored using staples and bags of soil, in the second year the polythene was anchored by dropping a relatively small amount of straw in the wheelings (1 kg per m). This proved largely successful; on the few beds and occasions when the straw became partially exposed only, this tended to occur from the anchor points at the ends (held by bags of soil) rather than the sides (which would not be an issue on a field scale) or towards the end of the trial in the spring when the straw dried out at one of the sites.

This treatment could feasibly be implemented by using a wider polythene sheet (2.5 m) and with modifications to existing straw laying machinery: setting up so that the polythene unrolls over the top of a reduced quantity of straw and redirecting a small proportion of the straw on top of the polythene to provide anchorage.

Closed-cell PE foam (Treatment F)

The treatment was included as a non-straw alternative. This treatment consisted of a single 7.5 mm thick natural/white closed-cell polyethylene foam laid directly over the crop and secured with a wider layer of white polythene. The material is relatively expensive and would only be cost-effective if re-used. It is available in different thickness, but thicker versions increase cost, we therefore examined the thinnest version with a view to using it on its own for earlier harvests or as an adjunct to other materials. The great advantage of this material is that the closed-cell nature (i.e. air is trapped in closed-cells) means that its insulation properties are unaffected by moisture. Based on the theoretical predictions it was expected that this treatment would have the lowest insulation value, and this proved to be the case, nevertheless it still provided adequate protection at all sites in both years, and we were able to recover it intact for re-use at the end of each year.

One aspect of this treatment not anticipated was that both it and the polythene cover were translucent, this meant that unlike in all the other treatments, the crop foliage remained green throughout, although this did not have any noticeable/measurable direct effect on crop quality either way. There was a perception that the presence of green foliage encouraged a higher slug population at one of the sites in 2015-16, but this was not seen in the 2016-17 trial.

The more translucent nature may also have contributed to a 'greenhouse' effect contributing to the relative higher increase in incoming U-value compared to the other treatments.

Fibre only (Treatment G)

This treatment was examined in the second year, and envisaged as the simplest way to make use of the cellulose-fibre on a commercial field scale. The product was loosely broken up and then blown onto the crop using a petrol leaf blower with a flexible outlet. The rate used (1.75 kg/m^2) was the same as used in the other fibre treatments, and intended to give a 5 cm depth of material. There was concern that the material would not stay in place on the crop without a cover, this proved to be unfounded. The carrot foliage trapped the initial fibres, and there was very little drift off the target bed. In addition, once the surface had been wetted by the first rain or dew following the initial application, the top layer of material formed a crust, and stayed locked in place for the duration of the winter until harvest.

In terms of frost protection, the material was equivalent to the field standard (straw over poly or straw alone) with a comparable outgoing U-value. Most of the winter the product remained quite wet and when temperatures were coldest, a frozen layer developed in the top 1-2 cm. The material is not quite so effective at preventing warm-up in the spring compared to the field standard. We presume this is because the overall mass was lower and therefore the maximum water content was also lower. Measurements in the first year indicated that the fibre can absorb up to 600% of dry weight in water when saturated, but at harvest was down to 27 to 75% depending on site.

Although not quantifiable, the crowns of the roots from under the fibre, had a better visual appearance than roots from the other treatments. We suspect that this may be due to its relative water absorbency, and freedom from micro-organisms.

From the practical perspective, this treatment is the most feasible non-straw alternative, providing equivalent frost protection to conventional straw, requiring less mass, and so less potential for nitrogen lock-up, better visual quality of the roots, and no risk of weed or disease introduction. It is likely that there could be several options for field application, depending on the form of delivery, and ease of adaptation of machinery. Different application methods would likely result in subtle differences in the structure of the layer, therefore additional trials would be appropriate to look at the influence of different application methods on performance.

Poly-over-fibre (Treatment H)

This treatment was examined in the second year and was essentially a modification of the poly-fibre sandwich (treatment E) from the first year, modified by removal of the bottom layer of polythene, as it was found that due to the smooth surface of the polythene, the fibre tended to fall off the shoulders of the beds, resulting in an variable depth or absence of insulation material in places. Removing the bottom layer resulted in improved and even coverage. The polythene over the top was intended to (a) keep the material in place, i.e. preventing it blowing away and (b) keep the material drier than in the fibre-only treatment (G), and this was indeed the case.

In terms of frost protection, the material had a slightly higher outgoing U-value than the field standard (straw over poly or straw alone) or fibre-only. This is probably a result of the lower moisture content providing less thermal mass and protection via latent heat. The material is not quite so effective at preventing warm-up in the spring compared to the field standard, with similar incoming U-values to the fibre-only and poly-over-reduced-straw.

Given that that this treatment did not provide any insulation benefit compared to the fibre-only, and that the fibre-only stayed in place without a cover, there is no justification for the additional cost and extra complication of covering the fibre with a layer of polythene.

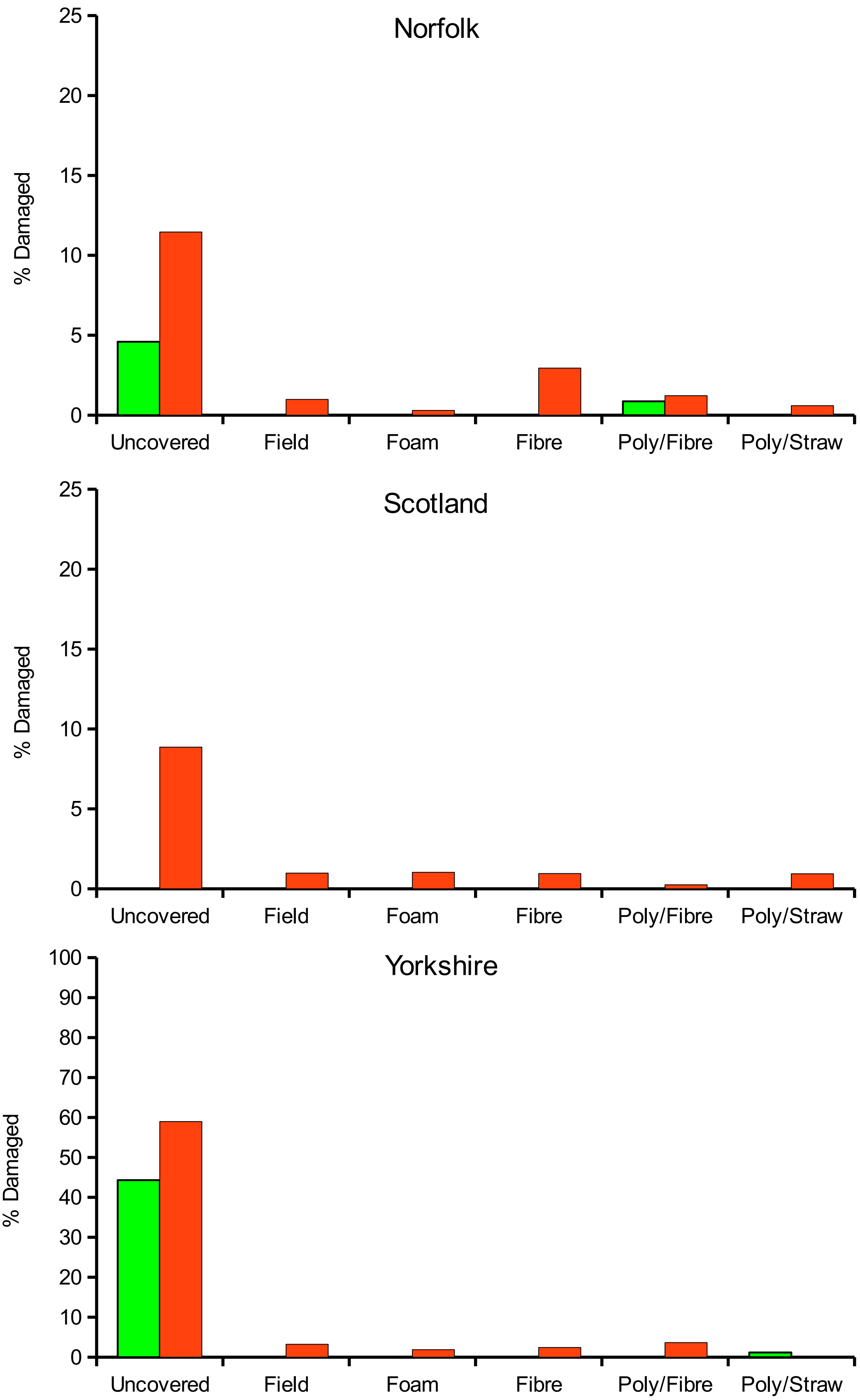


Figure 2. The percentage of damaged carrot roots at each harvest in each treatment at each site in 2016-17. Green (left hand) bars represent the first harvest, red (right hand) bars represent the second harvest.

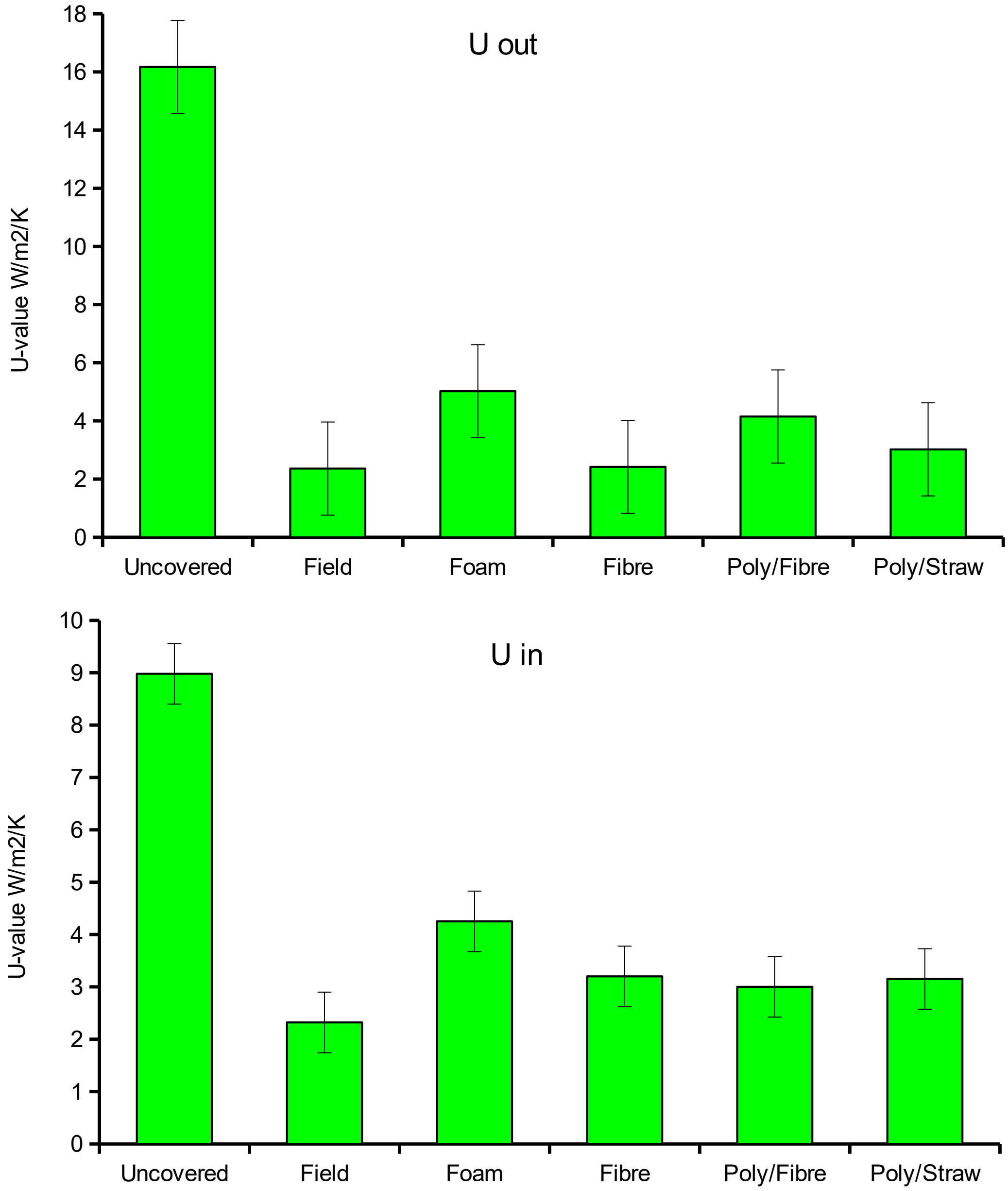


Figure 3. The effect of treatment on the estimated outgoing (soil losing heat) and incoming (soil gaining heat) U-values in 2016-17. A low U-value indicates a good insulator. Error bars represet the standard error of the mean.

Conclusions

- All treatments provided effective 'insulation' in both years of the trials (2015-16 and 2016-17).
- Although the current straw treatments are inefficient in pure insulation terms, it is likely that a significant part of the frost protection provided results from retention of

water in the straw-layer. This provides a greater thermal mass (reducing temperature fluctuations) and reduces freezing due to latent heat of fusion.

- Having a layer of polythene below the straw as well as providing another layer of insulation results in greater water retention in the straw layer, increasing its thermal mass, and increasing the potential for evaporative cooling.
- There is no evidence that light-exclusion by the polythene has any impact on crop quality.
- Covering straw with polythene allows the amount of straw to be reduced by about 2/3, whilst achieving a better level of insulation.
- The two non-straw alternatives: cellulose fibre and closed-cell PE foam both provided adequate frost protection.
- Closed-cell PE foam could easily be used as a supplemental layer in the current system if straw is in short supply.
- Cellulose fibre or similar material could provide a realistic alternative to straw, with no risk of weed introduction, reduced potential for nitrogen lock-up, and good crop quality.

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.

We have identified that a reduction in straw usage of up 2/3 could be achievable by using 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.

Unfortunately, whilst providing a realistic practical alternative in insulation terms, the current price of the cellulose fibre used in the study (£480 per t) makes it unlikely to be economic at the present time, but there may be potential for growers to source similar materials locally at lower cost.

Action Points

- Growers wishing to reduce straw usage could consider moving to a poly-over-straw using 1/3 the normal amount of straw.
- Growers able to economically source local sources of cellulose fibre or equivalent, could consider field scale trials.

SCIENCE SECTION

Introduction

Current 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 an additional layer of polythene below) 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 problematical and challenged as a sustainable technique. This is 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, and the potential for introduction of problems weed seeds with the straw. Supplies of straw are likely to become both more expensive and erratic in future years due to 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. In addition, landowners have a major concern that importing straw may introduce blackgrass seeds into fields which have been previously free. Although not considered a severe problem on sandy (carrot) soils, there is a fear that once present on a farm it could move on to other fields with heavier soil.

There is therefore a demand to examine alternative options for in-field storage of carrots which do not rely on the use of large quantities of straw: either through reduced quantities of straw or non-straw alternatives. A previous project, FV398a (Roberts & Lacey 2014), primarily a theoretical desk-based study, investigated:

- heat transfer principles involved in field storage
- the theoretical insulation value of current methods
- the cost and issues involved in using alternative insulation materials

The project identified inefficiencies (in terms of insulative value) in the current straw-based systems, some possible misconceptions, and alternative systems and materials that could have equivalent or better insulative value to the current system. However, estimates of insulative value of alternative systems were theoretical.

This project aims to:

a) Validate the theoretical insulative values for alternative materials and their impact on crop quality; and

b) Investigate practical implementation of alternative systems.

The detailed methods and results for the first year of the project (winter 2015-16) are given in the FV 398b annual report (Roberts & Howell, 2016) but are also fully reported here. In the first year, as well as an uncovered control, the two standard field treatments in current use (straw alone, and straw over polythene) were compared with a reduced-straw polythene sandwich, a cellulose fibre polythene sandwich, and closed cell PE foam. Based on experience in the first year, some of the treatments were modified for the second year in order to make them more practical to implement on a field scale.

Materials and methods

Treatments

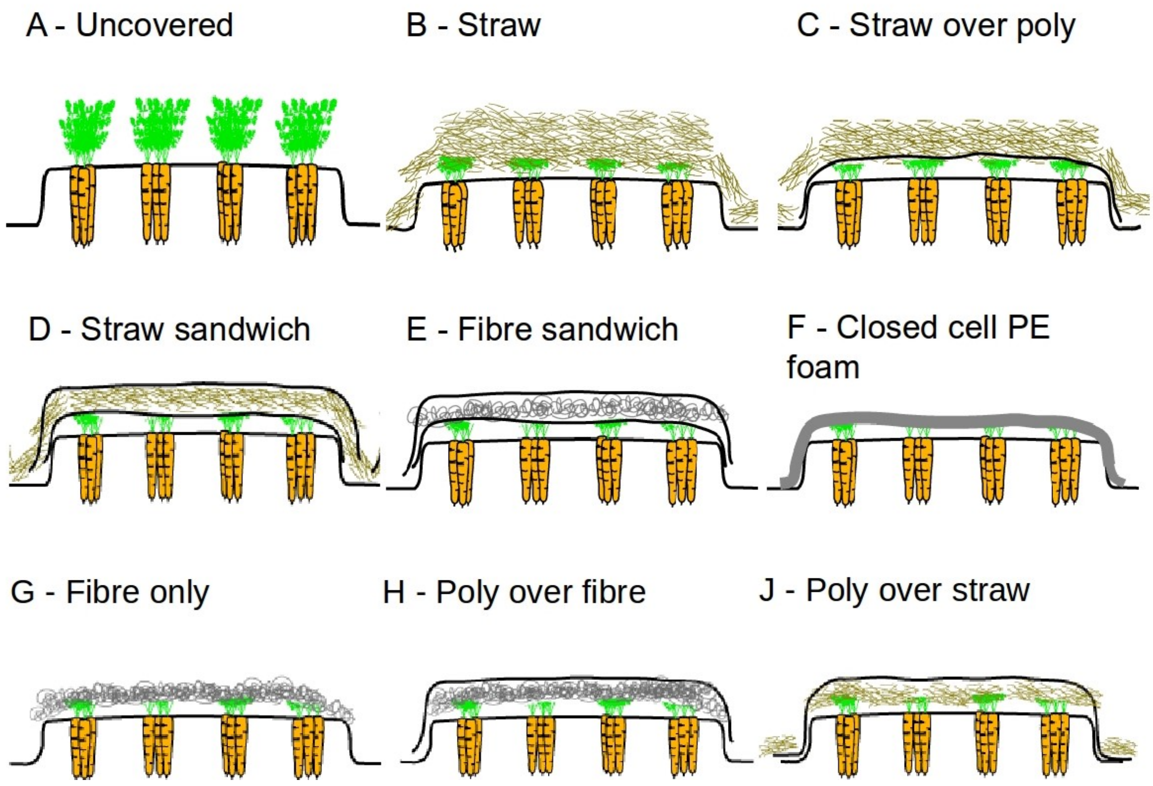
Following discussion with the grower representative and AHDB technical manager, six treatments were agreed for the trial in the first year (A-F). Based on experience in the first year, some treatments were modified for the second year, again following discussion with the grower representative and AHDB technical manager (A, B or C, F, G, H, J). The thinking behind the modifications is included in the discussion.

Table 2. Treatment codes and details for both years of the trials.

Year	Code	Treatment	Details/Notes
1 & 2	A	Uncovered control	Untreated control.
1 & 2	B	Straw alone	Standard covering of straw (3.7 to 8.3 kg/m^2) (commercial standard). All sites in year 1, one site in year 2.
1 & 2	C	Straw over polythene	Straw (2.8 to 6.9 kg/ha) with a single layer of black polythene below (commercial standard for prolonged storage). All sites in year 1, two sites in year 2.
1	D	Reduced straw polythene sandwich	Reduced amount of straw (~1.5 kg/m^2) with layer of black polythene below and layer of black polythene over the top. Year 1 only, modified for year 2 → J.
1	E	Cellulose fibre polythene sandwich	Cellulose fibre, approx. 5cm depth, 1.75 kg/m^2 with a layer of black polythene below and a layer of white polythene over the top. Year 1 only, modified for year 2 → H.
1 & 2	F	Closed cell PE Foam	Natural/white coloured closed cell polyethylene foam, 7.5mm thick, with a layer of white polythene over the top to provide anchorage. All sites in both years, material stored and re-used in year 2.
2	G	Cellulose fibre	Cellulose fibre, approx. 5 cm depth, 1.75 kg/m^2. Blown onto beds. Year 2 only.
2	H	Cellulose fibre with polythene cover	Cellulose fibre, approx. 5cm depth, 1.75 kg/m^2. Blown onto beds, then covered with black polythene. Year 2 only.
2	J	Reduced straw with polythene cover	Reduced amount of straw (~1.5 kg/m^2) covered with black polythene, plus straw in wheelings to anchor. Year 2 only.

1	X	Black fleece	Black fleece, one site only, limited temperature records.
1	XP	Black fleece polythene	Black fleece covered with a layer of polythene, one site only, limited temperature records.

Figure 4. Diagram demonstrating each of the treatments



Trial sites and layout

In the first year the three trial sites in different parts of the UK were: Norfolk (North Walsham), Yorkshire (West Knapton), Aberdeenshire (West Fingask). In the second year sites were located in similar areas, but in different fields: Norfolk (Southrepps), Yorkshire (Scampston), Aberdeenshire (East Lediken). Trial crops were selected on the basis that they were designated for the longest term storage to maximise the potential information obtainable.

In the first year at each site, growers covered their crop according to their normal practice. A uniform area of the crop was then selected as the trial area and divided into six plots of six to eight beds wide by 10 m long, arranged as three plots long by two plots wide. In the second year growers again covered their plots according to their normal practice, except that at two sites (Norfolk and Yorkshire), plot areas were marked in advance and some plots were left uncovered as appropriate (i.e. treatments A, F, G, H). Treatments were assigned to plots using a randomised block design, with each site being considered a block.

Where necessary, straw was carefully cleared from plots by hand (to avoid damage to any exposed crowns) and replaced with the appropriate materials after installing temperature and moisture sensors in each plot.

At two sites in each year the field standard was straw over poly (treatment C), and at one site the field standard was straw alone (treatment B). In each case for the other standard (i.e. B or C), a comparable amount of straw was used as in the standard field treatment. In year 2, there was only a single 'field standard' (either B or C) at each site.

For treatment D in year 1, the cleared bed was covered with a layer of black polythene (40 µm); dry straw was weighed into large woven sacks and then spread on an appropriate length of bed (3 kg per m of bed) to ensure consistent application rate of approx. 1.5 kg/m^2 across sites. The straw was then covered with another wider (2.5 m) layer of black polythene.

For treatment E, the cellulose fibre (Subcel F8000N, CIUR (UK) Ltd) was delivered in 14 kg bags of compressed product, so that prior to spreading the fibre was 'fluffed-up' either by hand at the Norfolk site, or in advance by an insulation blower for the other two sites. A layer of black polythene was un-rolled over each bed, then covered with the fibre and a layer of white polythene was immediately un-rolled over the top.

For treatment F, the foam and polythene cover were unrolled over the length of each bed and cut to length.

In each of treatments D, E and F, the top layer of polythene was anchored down using a combination of soil-filled bags and galvanised steel ground-cover staples at approx. 1.1m intervals.

For treatment G in year 2, cellulose fibre was delivered in 10 kg bags, slightly less compressed than used in the first year. Bags were broken up roughly by hand with a fork and blown onto the beds using a modified two-stroke petrol leaf blower in vacuum mode. The blower was modified by connecting a 10 m length of 80 mm diameter flexible ducting to the outlet side of the blower. The fibre was distributed by walking up and down the bed with the outlet of the ducting. Prior to applying the fibre, the foliage was flattened slightly by gently rolling with PE foam.

Treatment H in year 2 was a modification of year 1 treatment E by removal of the lower layer of polythene. The fibre was blown onto each bed as for treatment G, and then covered with a wide (2.5 m) layer of polythene anchored as in year 1.

Treatment J in year 2 was a modification of treatment D by removal of the lower layer of polythene. For each bed approx. 2/3 of the straw was removed together with the polythene.

The remaining 1/3 spread over the length of the bed. The straw was then covered with a wide (2.5 m) layer of black polythene. The ends of the polythene were weighed down with bags of soil and straw was dropped into the wheelings (approx. 1 kg/m) to anchor the polythene down.

In year 1 (2015-16), at the Yorkshire site only (i.e. without replication) two additional treatments were also examined on a speculative basis and without the detailed temperature records. These treatments consisted of a black thermal fleece alone (X) or with an additional cover of black polythene (XP).

Sensors and data records

A 60 cm Aquacheck (AquaCheck (Pty) Ltd, South Africa) sub-surface combined soil-moisture and temperature probe was installed vertically in one of the central beds of each plot at each site. These probes measure soil moisture and temperature at 10 cm intervals along their length, i.e. at 10 cm depth intervals when positioned vertically.. A soil auger was used to make a hole slightly larger than the diameter of the probe, and the extracted soil retained. The probe was then inserted and the hole backfilled with a slurry of water and the extracted soil. Probes were inserted so that the uppermost sensor was approximately level with the soil surface. At the Scottish site in the first year, the soil depth was too shallow to fully insert the probes so they were inserted with the second sensor approximately level with the soil surface. Pairs of probes were then connected to a weather station/data-logger that sent the data to a central sever via the mobile phone network. In addition to soil moisture/temperature, air temperature was also recorded at each site. The weather stations were powered by a lead-acid battery charged via a solar panel. In order to provide extra reliability, and data security during the winter (when light levels may not be sufficient to fully recharge the batteries), the data-loggers were equipped with an insulated external battery box that enabled two batteries to be connected in parallel. Data was measured and logged at hourly intervals. A number of repeat visits were needed to each site in each year to service/maintain the data-loggers.

In addition, to provide a backup, an additional set of temperature sensors (Maxim DS18B20. encased in a waterproof stainless steel tube) were installed in each plot at depths of approximated 0, 10, 30 and 40 or 50 cm. These sensors were connected on a single ‘one-wire' network bus and connected to a prototype Arduino based data-logger. These loggers were powered by a lithium chloride battery charged by a solar panel, and sent data to a central server via the mobile-phone network. Data was measured and logged at 30 min intervals.

Harvesting

At each site, a sample was harvested from each plot on two occasions: the first in late Jan or early February, and the second just prior to the main field harvest by the grower (Table 3).

In each case the insulation was opened up around the mid-point of one of the central beds, and the carrots dug by hand with a fork from either a 1.25 m or 2 m length of bed. The length of bed harvested was adjusted between sites depending on the crop density to ensure an adequate number of roots was assessed (i.e. >200). Carrots from the outer two rows were harvested separately from carrots in the inner row or rows. Roots were lightly brushed by hand to remove excess soil and stored in paper sacks at ambient temperature until processing (within 48 h).

After harvest, all carrots were transported to VCS facilities, washed, weighed and counted. Individual roots were then scored for freezing damage (0-3 scale), cavity spot (presence/absence), and presence of crown rots. A sample of carrots from each plot was also sent to ALS Food and Pharmeceutical or Scientific Analysis Laboratories Ltd for sugar and dry matter analysis.

Data handling and analysis

Harvest data

The numbers of frost-damaged and crown-rotted roots were analysed by fitting a series of generalised linear models to the data to produce an analysis of deviance using Genstat (Payne *et al.*, 2005). Models were specified with a logit link function and binomial error distribution. Means and confidence limits were calculated as predictions after fitting the appropriate model.

Marketable yield was calculated as the total yield multiplied by the proportion of undamaged roots (in year 1) and total yield minus the weight of damaged roots (year 2). Total yield and marketable yield were subject to analysis of variance using Genstat (Payne *et al.*, 2005).

Temperature data

Up to a million data records were accumulated from the various sensors each year. Due to the volume of data, calculations of temperature changes, heat loss, heat flux, and effective U-values were done at the server level. Data were saved in a MySQL database on the server. Specific scripts were written in PHP (a computer programming language) to extract the data from the database, and perform calculations of the various relevant parameters.

First the change in temperature, ΔT, since the previous reading and the time interval was calculated for each sensor, for each record (i.e. hourly, except for occasional missing values). In addition, because the surface sensor was not always precisely located at the surface, where necessary quadratic interpolation was used to provide an estimate of the surface temperature.

The volumetric heat capacity of the soil, C_v, was calculated using the recorded % moisture values, and standard values for a sandy soil:

$$C_v = (q_s \times \rho) + (c_p \times \%M/100)$$

Where:

q_s is the specific heat capacity of quartz/sand (0.834E3 J/kg)

ρ = is the bulk density of the soil (1.6E3 kg/m^3)

c_p is specific heat capacity of water at 5°C (4.2E6 J/m^3)

%M is the percentage moisture in the soil

The heat loss (negative) or heat gain (positive) per unit area, *qa*, in each layer of soil was then calculated as:

$$qa = C_v \times (\Delta T_1 + \Delta T_2)/2 \times (z_1 - z_2) \text{ J/m}^2$$

Where ΔT_1 and ΔT_2 are the changes in temperatures in the soil at depths z_1 and z_2 respectively.

The total heat loss or gain from the whole soil profile was then calculated as the sum of the changes in each layer, i.e.:

$$QA = \Sigma qa \text{ J/m}^2$$

The heat flux at the soil surface, *G,* was then calculated by dividing by the time in seconds as:

$$G = QA/time \text{ W/m}^2$$

Finally an 'effective' U-value was calculated as:

$$U = G/|(AT - ST_0)| \text{ W/m}^2\text{/K}$$

Where *AT* and ST_0 are the air temperature (measured in °C at approximately 60 cm above the soil surface) and temperature at the soil surface respectively.

For statistical analysis, values for heat loss were summarised for full months and the monthly data analysed as independent measures, by analysis of variance.

Results

Details of each of the sites are shown in Table 3.

Table 3. Basic details for each trial site.

Site	Drilled	Variety	Trial set up	Harvest 1	Harvest 2	Day °C < 0[1]
Year 1 (2015-16)						
Norfolk (N. Walsham)	29/05/15	Nairobi	10/11/15	11/02/16	29/02/16	3.4
Aberdeenshire (W. Fingask)	18/05/15	Nairobi	20/11/15	10/02/16	04/05/16	21.3
Yorkshire (W. Knapton)	05/03/15	Nairobi	25/11/15	11/02/16	27/04/16	6.0
Year 2 (2016-17)						
Norfolk (Southrepps)	07/06/16	Nairobi	26/10/16	25/01/17	27/04/17	3.5
Aberdeenshire (East Lediken)	~05/16	Nairobi	08/11/16	24/01/17	03/05/17	16.2
Yorkshire (Scamspton)	29/04/16	Nairobi	26/10/16	25/01/17	26/04/17	13.3

Notes:
[1] No. of degree-days of air temperature below 0 °C, calculated as the number of hours when air temperature was below 0 °C divided by 24.

Frost damage and crown-rots

It was impossible to distinguish between crown rots resulting from frost damage and crown rots resulting from other factors (e.g. slug damage, disease) at the time of assessment, therefore the data for frost damage and crown rots were combined into a single measure of damaged roots for analysis. However, notes were also made in the field.

Year 1 (2015-16)

Results for the first year are shown in Figure 5. Analysis of deviance indicated significant differences between sites, treatments, a site x treatment interaction, and harvest date and indication of an effect of bed position. In essence the only significant (frost) damage occurred in the uncovered treatment (A) in Scotland and in the uncovered (A) and fleece covered (X and XP) plots in Yorkshire. There were lower levels of crown rots in most of the covered treatments in Yorkshire: these were not associated with frost damage but were noted as being associated with slug damage at the time of harvest, and the absence of any residual foliage (presumed to have been eaten by the slugs)

Year 2 (2016-17)

Results for the second year are shown in Figure 6. Analysis of deviance indicated similar effects to year 1, with significant differences between sites, treatments, a site x treatment interaction, and harvest date and indication of an effect of bed position. All of the cover treatments provided adequate protection from frost damage, with the only significant frost damage occurring in the uncovered plots. A low level of non-frost damage was seen in all covered treatments at the second assessment but this did not differ between cover treatments.

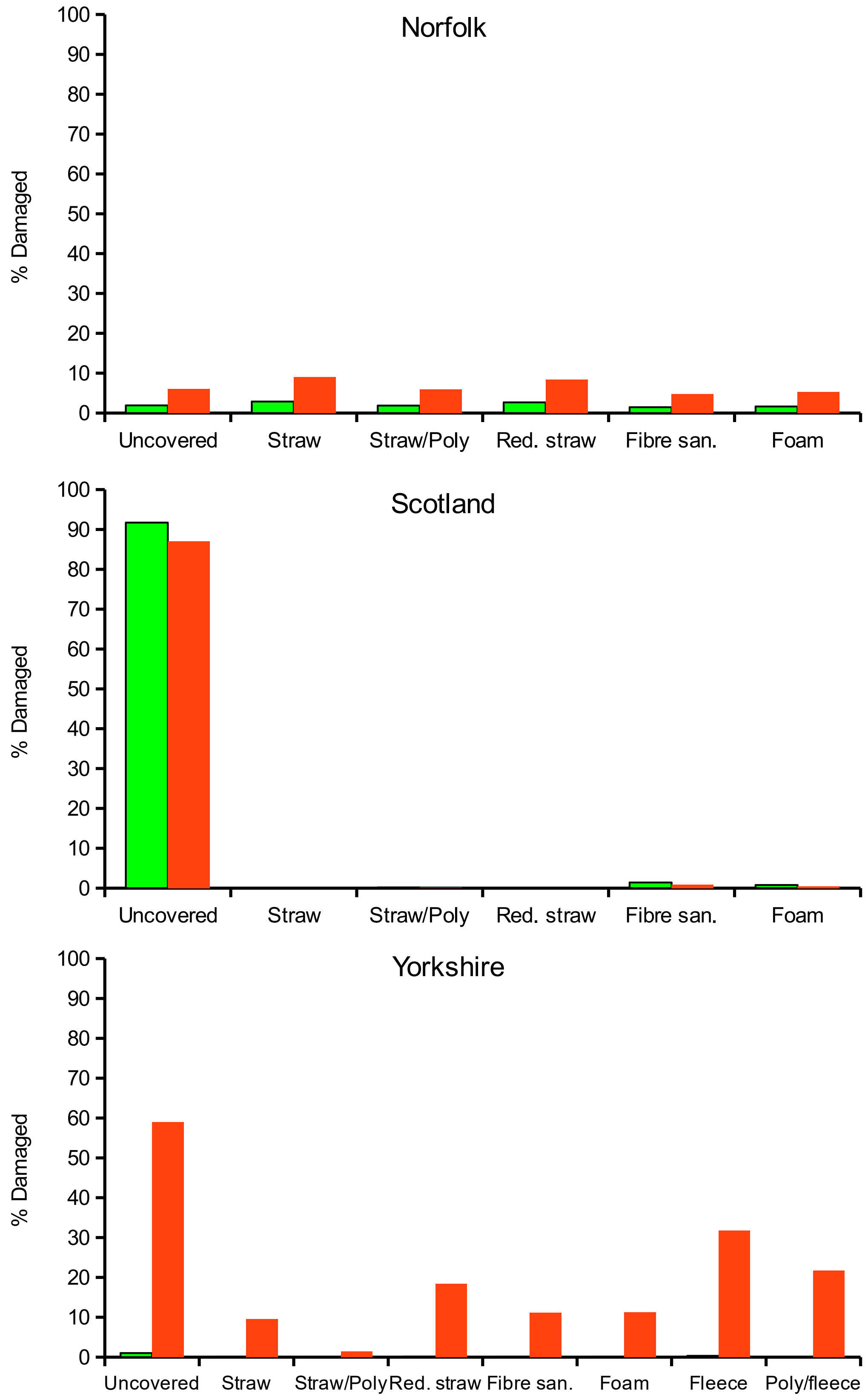


Figure 5. The percentage of damaged carrot roots at each harvest in each treatment at each site in year 1 (2015-16). Green (left hand) bars represent the first harvest, red (right hand) bars represent the second harvest.

Cavity spot

In year 1 (2016-16), cavity spot differed significantly between sites, with minimal levels recorded in Norfolk and Scotland and very high levels in Yorkshire (resulting in premature harvest of the surrounding crop). There were no consistent effects of the treatment on levels of cavity spot.

In year 2 (2016-17), there were again significant differences in cavity spot between sites and between harvests, with minimal levels recorded in Norfolk and higher levels in Scotland and Yorkshire, and higher levels at the second harvest, particularly in Scotland. However, unlike the first year, there appeared to be a significant effect of treatment, with cavity spot levels significantly higher under the two straw treatments. Given the lack of within site replication, and the likely patchy distribution of cavity spot within fields, we should be cautious about interpreting this a real treatment effect.

Yield

Year 1 (2015-16)

The marketable yields for each treatment and site in year 1 are shown in Figure 7. Analysis of variance indicated significant effects of site, treatment, and harvest date and a site x treatment interaction. Overall yield was greatest at the Yorkshire site and lowest at the Norfolk site, and lower at the second harvest date than at the first. Yield was significantly reduced in the uncovered plots in Scotland and in Yorkshire at the second harvest, and in the fleece covered plots at the second harvest in Yorkshire. Significant reductions in both yield and marketable yield occurred where there was significant frost damage.

Year 2 (2016-17)

The marketable yields for each treatment and site in year 2 are shown in Figure 8. Analysis of variance indicated significant effects of site, treatment and a site x treatment interaction. Overall yields were lower in Scotland, lower in the uncovered control treatment due to frost damage, particularly in Yorkshire, and did not differ amongst the covered treatments.

Sugars and dry matter

For both years, although there were significant differences between sites and harvest dates, there was no effect of treatments on sugar levels or dry matter.

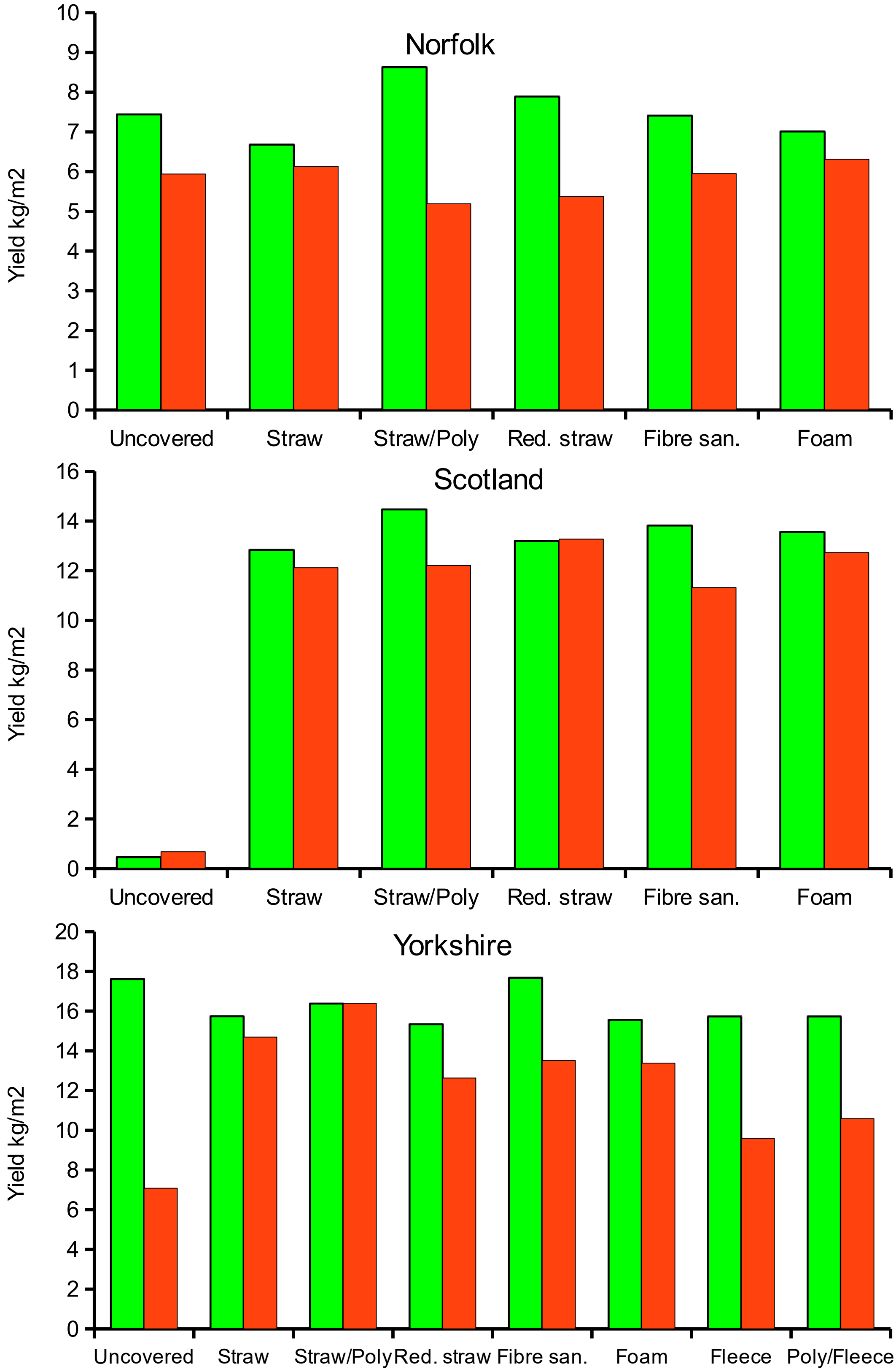


Figure 6. Effect of treatments on the marketable yield for each harvest date and site for year 1 (2015-16). Green (left hand bars) represent the first harvest, red (right hand bars) represent the second harvest.

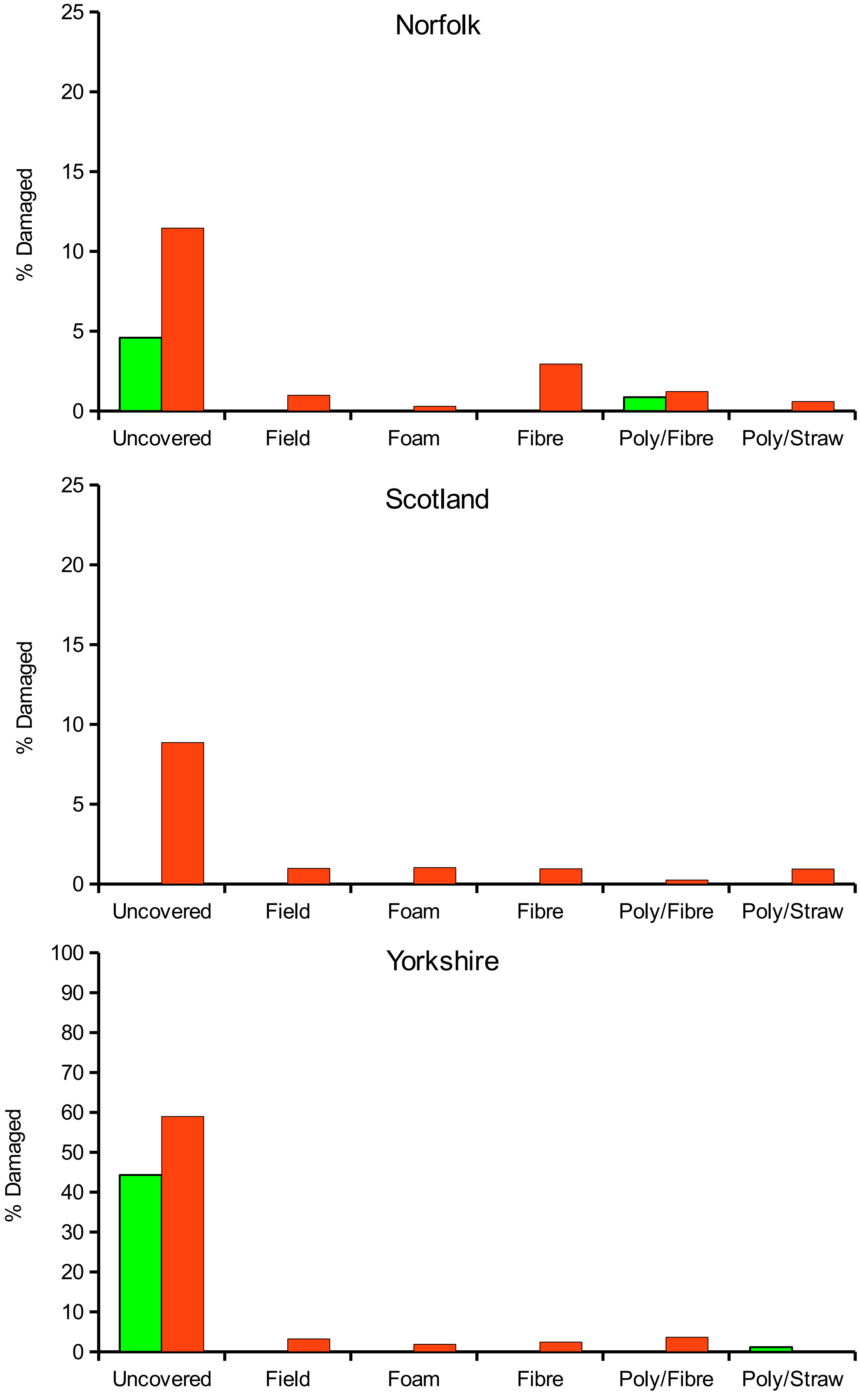


Figure 7. The percentage of damaged carrot roots at each harvest in each treatment at each site in year 2 (2016-17). Green (left hand) bars represent the first harvest, red (right hand) bars represent the second harvest.

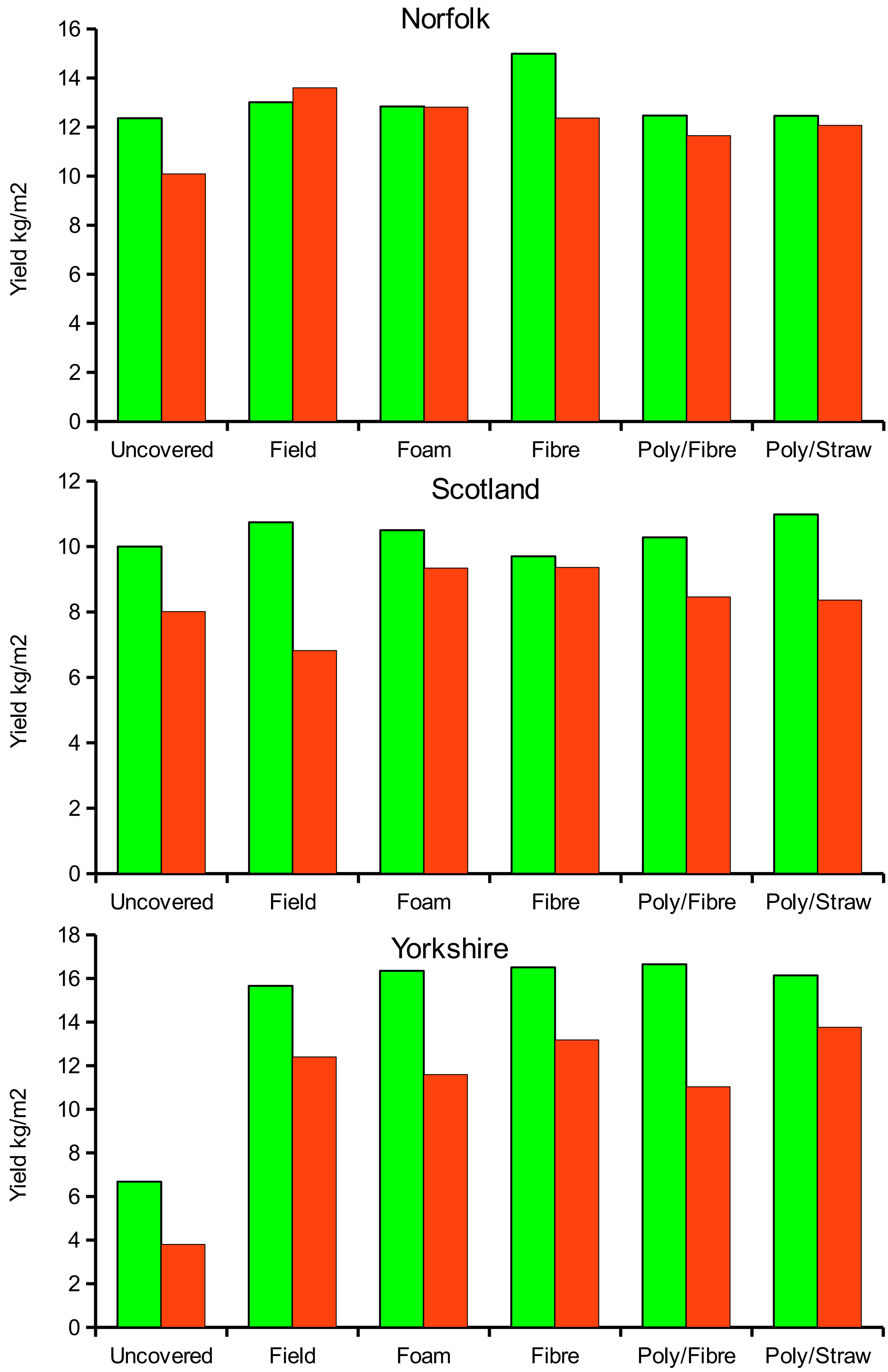


Figure 8. Effect of treatments on the marketable yield for each harvest date and site for year 2 (2016-17). Green (left hand bars) represent the first harvest, red (right hand bars) represent the second harvest.

Soil Moisture

Year 1 (2015-16)

Overall average soil moisture values varied between plots (treatments) within each site, but there were no consistent treatment effects. It is likely that in most cases this was a result of the precise placement of the probe and local variations in soil depth/composition and topography at each of the sites. However, there was an indication that the soil moisture was slightly higher for treatment B (Straw alone). In Scotland, at both harvest dates the soil in this treatment was noted as being ‘claggier’ and more difficult to remove from the roots than the other plots.

Year 2 (2016-17)

Overall there were no significant effects of treatments on soil moisture. At the Norfolk site, there was a tendency for the plots that were not covered with polythene (i.e. A - uncovered and G - fibre only) to be drier (data not shown).

Temperature

Year 1 (2015-16)

The min, max and mean soil surface temperatures and air temperatures at each site are shown in Figure 9. The lowest soil surface temperature recorded was -3.6 °C, in the uncovered plot in Scotland, and where slightly negative temperatures were also recorded in some of the covered plots.

The lowest air temperatures were recorded in Scotland with a minimum of -7.6 °C for the standard screened air temperature at a height of ~60 cm but also -9.8 °C at a height of ~10 cm above the uncovered plot.

All treatments significantly raised the minimum soil surface temperatures compared to the uncovered control, with treatment D (reduced straw poly sandwich) the best, followed by C, B, E, and F.

All treatments significantly reduced the maximum soil surface temperatures compared to the uncovered control, with indications that treatment C was the best (lowest maximum) and F the worst.

Year 2 (2016-17)

The min, max and mean soil surface temperatures and air temperatures at each site are shown in Figure 10. The lowest soil surface temperature recorded was -2.8°C in the uncovered plot in Scotland, where slightly negative temperatures were also recorded in the foam and poly/straw plots.

The lowest air temperatures were recorded in Scotland with a minimum of -7.7°C.

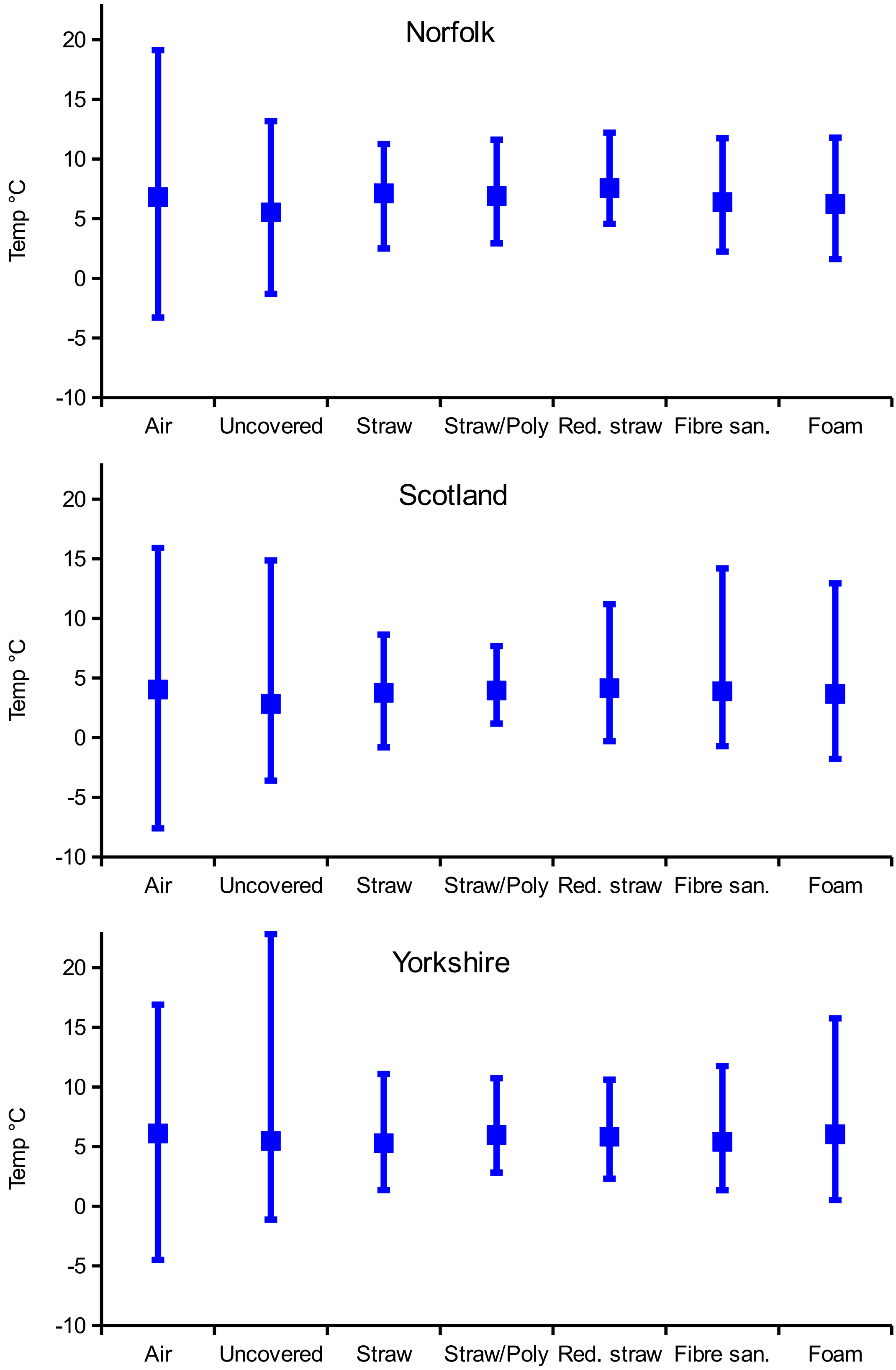


Figure 9. The effect of treatment on the soil surface temperature at each site in year 1 (2015-16). The square symbol represents the average, the bars represent the maxima and minima. Air temperature is also shown on the left for reference.

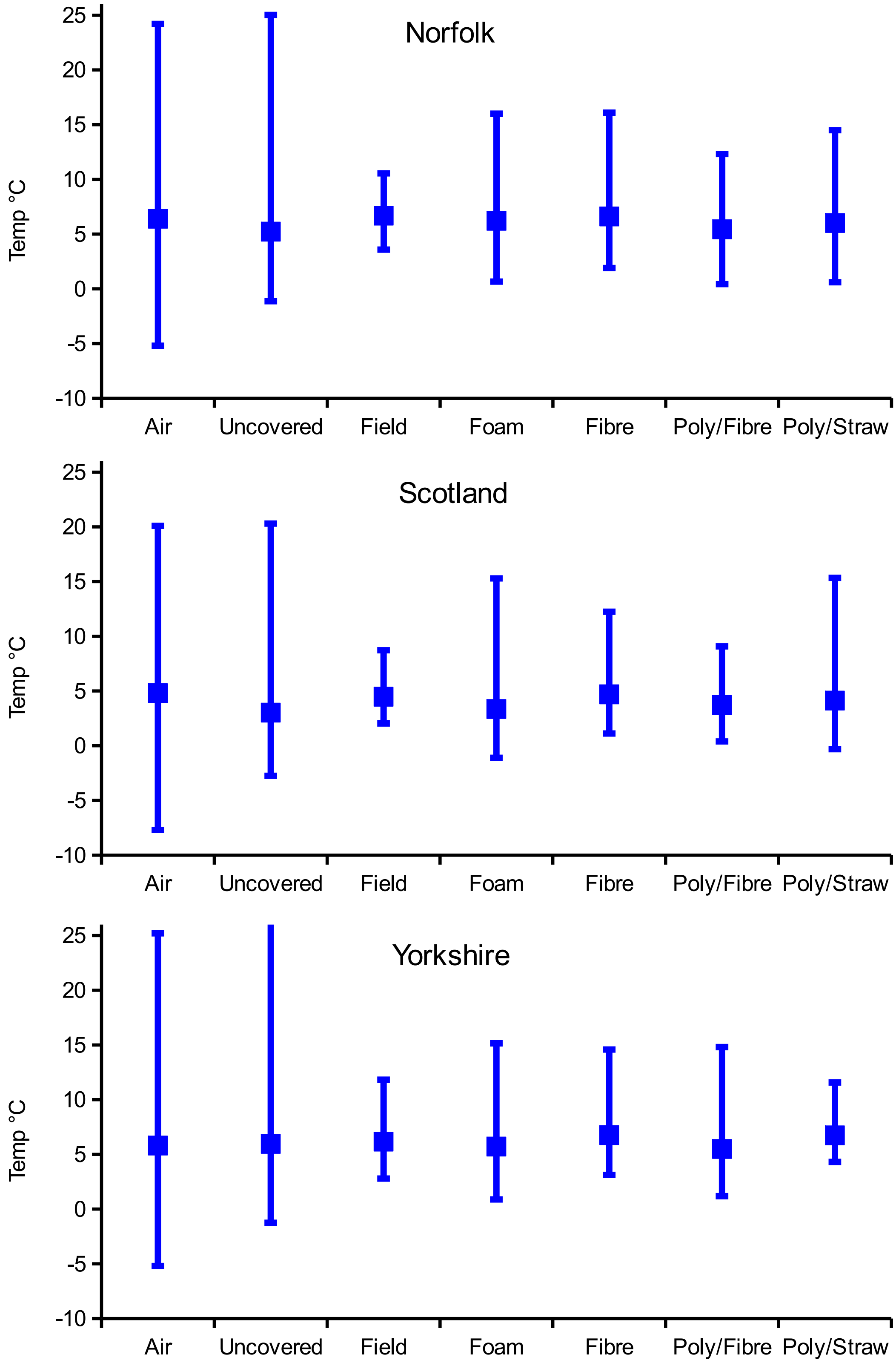


Figure 10. The effect of treatment on the soil surface temperature at each site in year 2 (2016-17). The square symbol represents the average, the bars represent the maxima and minima. Air temperature is also shown on the left for reference.

All treatments significantly raised the minimum soil surface temperatures compared to the uncovered control, with the field standard treatment (B or C), fibre-only (G) and poly/reduced straw (J) performing the best.

All treatments significantly reduced the maximum soil surface temperatures compared to the uncovered control, with indications that the field standard (B or C) and poly/fibre (G) performed the best. Spring warm up was more rapid for the foam (F) and fibre only (G) than the other treatments.

Insulation value

U-values in Watts per m^2 per Kelvin (W/m^2/K) provide a measure of the insulation value of a system, the lower the value the better the insulator. These were calculated separately for each hourly set of temperature and moisture values. The dynamic nature of the systems meant that calculation of meaningful effective values was problematical for some records (see discussion). Therefore values were averaged only when (a) the magnitude of the temperature difference was greater than 1°C and (b) when the sign of the temperature difference matched the direction of heat flow. Values were calculated separately for heat loss and heat gain by the soil.

Year 1 (2015-16)

U-values are summarised in Figure 11. All of the covers significantly increased outgoing insulation value (reduced U-value) compared to the control, the best level was achieved with treatment D (reduced straw-poly-sandwich), followed by C, B, E, and F (the same order as for minimum temperatures).

All of the covers significantly increased the incoming insulation value (reduced U-value) compared to the uncovered control. However the ranking of the treatment differed from the outgoing values, with treatment C (straw over poly) the best, followed by B, D, E and F.

Year 2 (2016-17)

U-values for 2016-17 are summarised in Figure 12. All of the covers significantly increased outgoing insulation value (reduced U-value) compared to the control, the best levels were achieved with field standard (B/C) and the fibre (G), the foam (F) performed the worst, but still provided adequate frost protection.

All of the covers significantly increased the incoming insulation value (reduced U-value) compared to the uncovered control (A). The field standard (B/C) gave the best (lowest) U-value, and foam the worst.

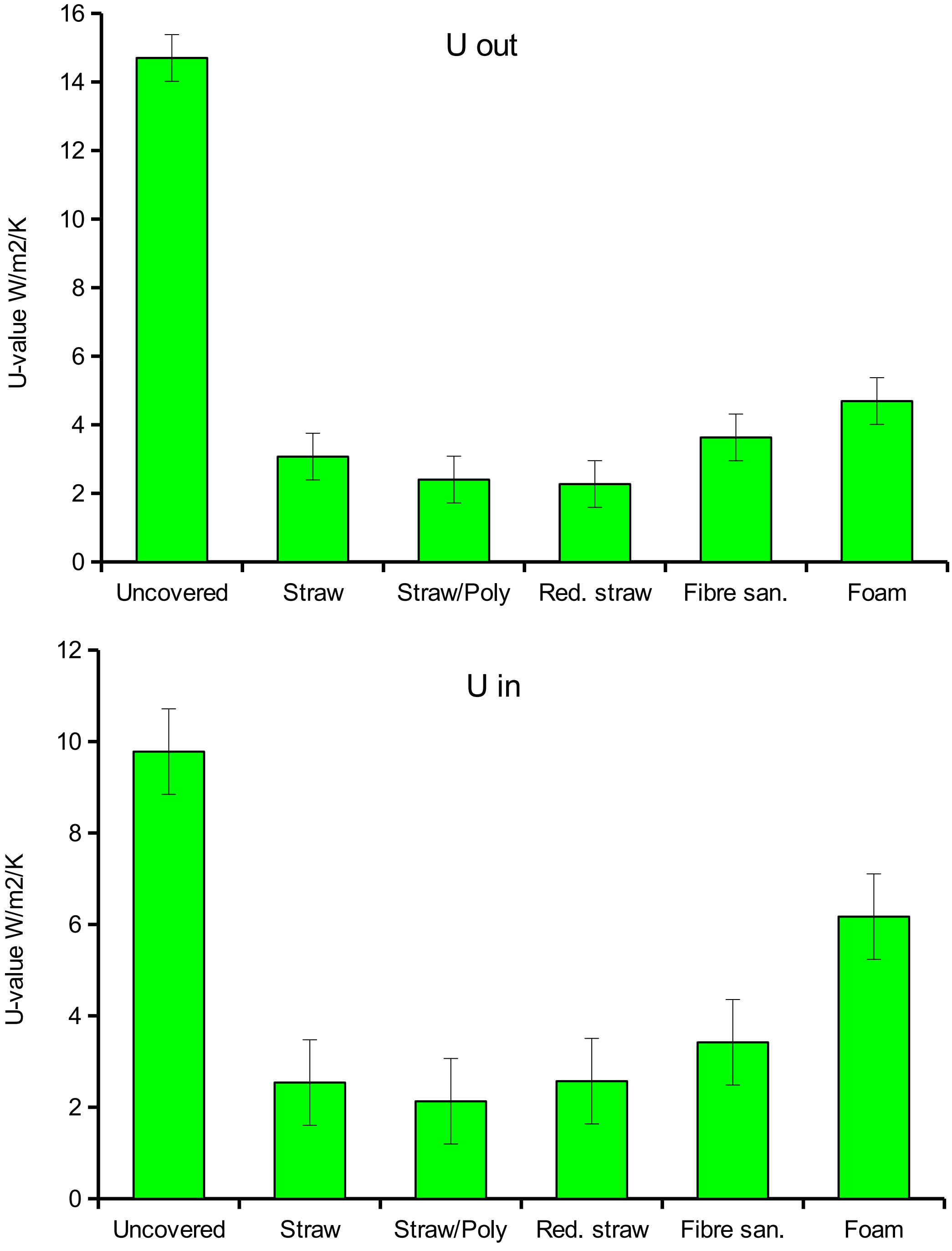


Figure 11. The effect of treatment on the estimated outgoing (soil losing heat) and incoming (soil gaining heat) U-values in year 1 (2015-16). A low U-value indicates a good insulator. Error bars represent the standard error of the mean.

Discussion

In both years of the trials and at all three sites, all of the main treatments provided effective insulation compared to the uncovered control and were effective in eliminating significant frost damage. This was reflected in the yield, proportions of damaged roots, the minimum soil-surface temperatures recorded and the calculated (outgoing and incoming) U-values.

Based on experience in the first year, some of the treatments were modified for the second year with a view to making them more practical for application on a commercial field scale.

The theoretical basis for measuring and comparing insulation values are presented in the previous project, FV398a (Roberts & Lacey, 2014). Calculation of U-values was problematical for some hourly records. On some occasions the soil continued to lose heat, even when the air temperature was greater than the soil temperature. This seems nonsensical, but would occur if the insulation layer is colder than both the soil and air, and/or if evaporation or melting of ice is occurring in the insulation layer (i.e. latent heat transfer), this would be highly likely where the insulation material is wet. On some occasions, the apparent U-values suddenly became extremely large (e.g. > 100 $W/m^2/K$), investigation revealed that this occurred when the temperature of the soil and air temperatures were very close (i.e. less than 1°C and often less than the expected accuracy of the sensors) making the divisor in the formula relatively small. To avoid these artefacts and produce more meaningful estimates, U-values were averaged only when (a) the magnitude of the temperature difference was greater than 1°C and (b) when the sign of the temperature difference matched the direction of heat flow.

Even given these restrictions, the U-values calculated from the data were larger than the theoretical estimates for each of the treatments. This is perhaps not surprising given that theoretical values are based on an ideal steady state system (i.e. constant temperatures, etc.). Although the differences between cover treatments were not statistically significant, in year 1, the out-going insulation values (i.e. U-values when heat was being lost from the soil) of each treatment were ranked in the following order: poly-straw-poly (D), straw-poly (C), straw only (B), poly-fibre-poly (E), foam (F). In year 2, the ranking order was field standard (B or C) equal with fibre-only (G), then poly-straw (J), poly-fibre (H) and foam (F). The in-coming (i.e. when heat was being gained by the soil) U-values were ranked in a slightly different order, in year 2: straw-poly (C), straw only (B), poly-straw-poly (D), poly-fibre-poly (E), foam (F). In 2016-17 they were ranked: field standard (B or C) followed by equal poly-fibre (H), poly-straw (J), fibre (G) and then foam (F). It would be expected that in-coming and out-going would rank similarly, but this may be due differing impacts thermal mass effects and evaporative cooling (see notes on individual treatments).

Notes and comments on each of the treatments are given below [cost calculations for different options were given in the previous project FV 398a (Roberts & Lacey 2014)]:

Uncovered (Treatment A)

This treatment was included as a negative control in both years and at all sites. Inevitably the harvested carrots had significant levels of frost damage, and marketable yields were reduced compared to the covered plots.

It would be expected that levels of frost damage would be correlated with the minimum temperatures at each site. This was the case in 2015-16 where the most severe damage occurred at the coldest site (Aberdeenshire). In 2016-17 the coldest site was again Aberdeenshire, but there was no frost damage at the first harvest (end of January) and damage was still at a relatively low level at the second harvest. The most severe frost damage was seen at the Yorkshire site. It is suspected that the most likely reason for the difference was due to exposure of the crowns. The crowns were generally at or below the soil line at the Scottish site, whereas at the Yorkshire site (with large roots destined for processing) crowns were exposed and often 1cm above the soil line. In addition (although not measured) it was perceived that there was a greater mass of foliage at the Scottish site which could reduce the rate of heat loss from the soil surface. This suggests that simply ensuring crowns are covered with soil (e.g. by choice of variety or by cultivating between rows to ensure they are) could eliminate the need for, or reduce the amount of straw required for earlier harvested crops.

Other factors, such as soil type and soil moisture also affect the thermal conductivity of the soil and so influence surface temperatures and the potential for frost damage. The greater the thermal conductivity of the soil, the more rapidly heat is moved up the soil profile to replace heat lost at the surface. Sand is a better thermal conductor than clay which is better than peat; and a wet soil is a better thermal conductor than a dry soil. Thus while we may perceive that a dryer soil is warmer (because it is actually a better insulator) the likelihood of frost damage will be less in a wetter soil.

Straw alone (Treatment B)

This treatment was included as a positive control and commercial standard, and to obtain baseline data for current practice. It was included at all sites in 2015-16 and one site in 2016-17. Growers tend to use straw alone for shorter term crops, or when the crop may be processed and some damage to crowns is acceptable. This treatment provided slightly less insulation than straw over polythene (treatment C). The straw remained wet at the bottom (but not as wet as treatment C), and based on moisture contents at the final harvest the water content was equivalent to up to 8 kg/m^2. This has two effects: providing a thermal mass effect (reducing temperature fluctuations, and the water in the straw will freeze before the soil/crop) and evaporative cooling. It is likely that both the thermal mass effect and the protection resulting from release of latent heat when water in this layer freezes are important aspects of the protection provided. In 2015-16 the soil in the beds was wetter in this treatment than the others which all had a covering of polythene, but this was not the case in 2016-17.

Straw-over-poly (Treatment C)

This treatment was included as a positive control and a commercial standard, to obtain baseline data for current practice and to understand more about the role and benefits or otherwise of the polythene layer. It was included at all sites in 2015-16 and at two sites in 2016-17. Growers planning long-term field storage of crops generally use a straw-over-poly system. The introduction of a polythene layer provides additional insulation through surface resistance to heat transfer, and so overall provides slightly greater insulation than straw alone (treatment B) (see Figure 11). However, the most important effect of the polythene was that the straw remains much wetter than treatment B (e.g. 7.7 vs 2.8 kg/m^2 at the Norfolk site in Feb. 2016), and often with free water on the surface of the polythene. Based on moisture contents of the straw at the final harvests the water content was equivalent to as much as 14 kg/m^2. This larger amount of water provides a greater thermal mass and greater potential for evaporative cooling. Thus, not only does this mean that the crop is more protected from freezing, but also heats up less slowly in the spring (i.e. is kept in a narrower temperature range than the other treatments. Hence treatment C appeared to be the most effective insulation against incoming heat (Figure 11).

In the previous project (FV398a) growers often reported that the main benefit of the polythene under straw was light-exclusion to prevent re-growth. We could find no evidence that light-exclusion prevents re-growth of carrots, and all the evidence suggests that it is entirely temperature driven. Experience in this project supports this: light exclusion did not prevent re-growth but simply resulted in more yellow and etiolated foliage rather than green normal foliage. We conclude that the beneficial effect of the polythene perceived by growers has little to do with light exclusion and is primarily a result of the greater thermal mass, and evaporative cooling effects, which in turn maintain soil and carrots at a lower temperature in the spring.

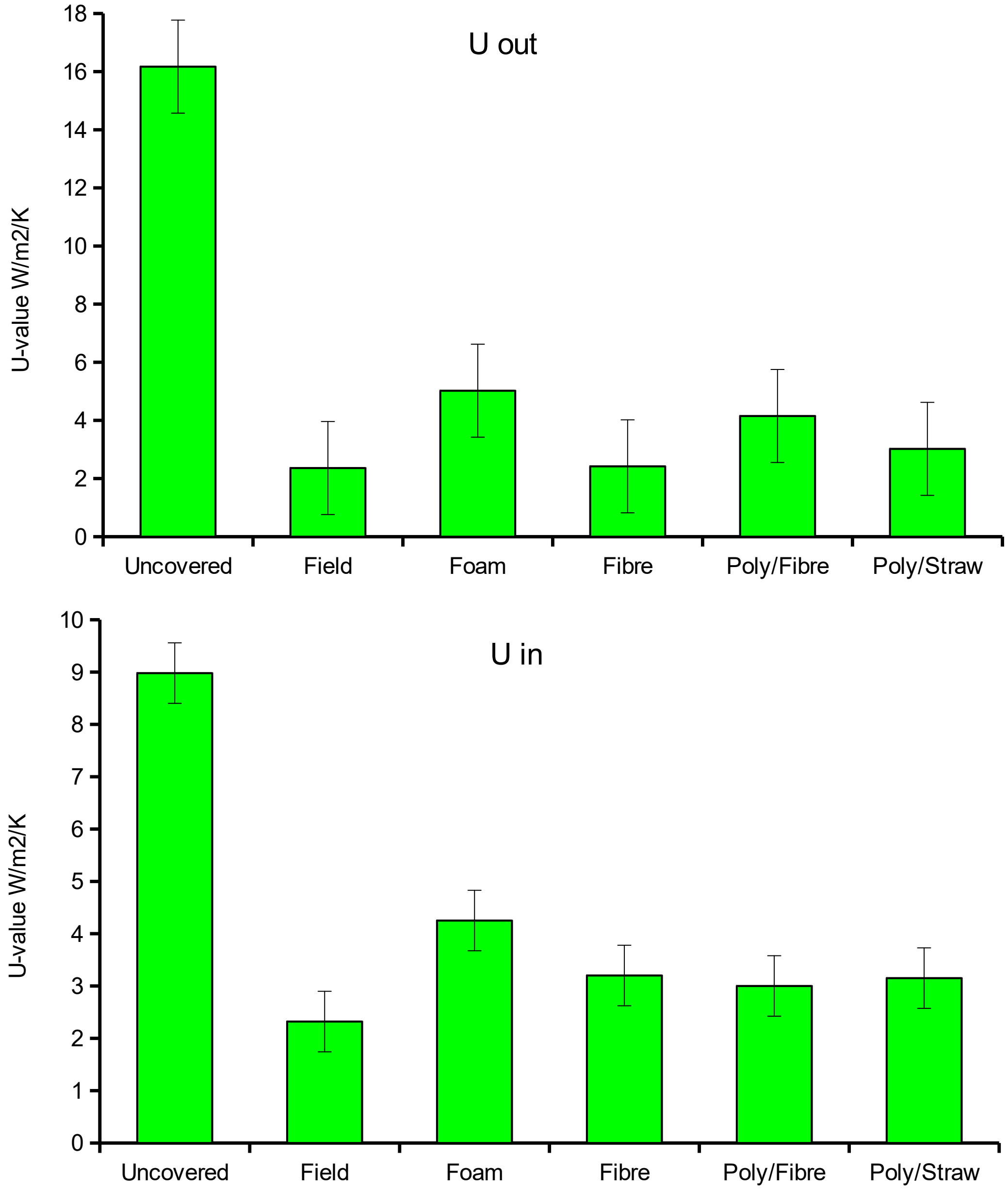


Figure 12. The effect of treatment on the estimated outgoing (soil losing heat) and incoming (soil gaining heat) U-values in year 2. A low U-value indicates a good insulator. Error bars represent the standard error of the mean.

Reduced straw poly sandwich (Treatment D)

This treatment was examined in 2015-16, when it provided the most effective insulation against heat loss from the soil. Theoretical estimates of U-values in the previous project (FV398a) indicated that the open surface of the traditional straw treatments was an inefficient use of the insulation material due to mass transfer of air and ingress of water. The estimates suggested that the amount of straw used per ha could be reduced by about 2/3 by putting the straw in a polythene sandwich. These results clearly support the earlier theoretical predictions. However, the presence of a moisture barrier over the top, means that in the spring there is no opportunity for evaporative cooling and so this treatment ranked behind straw-poly (treatment C) for incoming insulation value. It should be noted that the top covering was with black polythene, so there may also have been more direct radiation gain at the surface compared to the straw.

The intention of this treatment was that the straw should remain dry, it did not; although it was considerably drier than the other two straw treatments. Therefore in the second year this treatment was modified to become poly-over-reduced-straw (treatment J).

Poly over reduced straw (Treatment J)

This treatment was examined in the second year only (2016-17), and was considered a modification of the reduced-straw polythene sandwich of the first year (2015-16), simplified by omission of the polythene layer below the straw and using a minimal amount of straw in the wheelings to anchor the polythene.

The omission of the lower layer of polythene made little difference to the insulation values whilst reducing costs and making it more practical for field scale deployment. Whereas in the first year the top layer of polythene was anchored using staples and bags of soil, in the second year the polythene was anchored by dropping a relatively small amount of straw in the wheelings (1 kg/m). This proved largely successful; on the few beds and occasions when the straw became partially exposed, this tended to occur from the anchor points at the ends (held by bags of soil) rather than the sides (which would not be an issue on a field scale) or towards the end of the trial in the spring when the straw dried out at one of the sites.

This treatment could feasibly be implemented by using a wider polythene sheet (2.4 m was used in the trials) and with modifications to existing straw laying machinery: setting up so that the polythene unrolls over the top of a reduced quantity of straw and redirecting a small proportion of the straw on top of the polythene to provide anchorage. It would result in a direct cost saving compared to conventional treatments, equivalent to the saving in the cost of straw minus the increased cost of the wider polythene. This is typically estimated to be around £2000 per ha.

Closed-cell foam (Treatment F)

The treatment was included as a non-straw alternative. This treatment consisted of a single 7.5 mm thick natural/white closed-cell polyethylene foam laid directly over the crop and secured with a wider layer of white polythene. The material is used by the building trade to provide frost protection for newly laid concrete, but it is relatively expensive (3 to 5x the cost of straw) and would only be cost-effective if re-used several times. It is available in different thickness, but thicker versions increase cost. We therefore examined the thinnest version with a view to using it on its own for earlier harvests or as an adjunct to other materials. The great advantage of this material is that the closed-cell nature (i.e. air is trapped in closed-cells) means that its insulation properties are unaffected by moisture. Based on the theoretical predictions it was expected that this treatment would have the lowest insulation value, and this proved to be the case. Nevertheless it still provided adequate protection at all sites in both years, and we were able to recover it intact for re-use each year at all sites.

Both the foam and the polythene cover were translucent. This meant that, unlike in all the other treatments, the crop foliage remained green throughout. This did not have any noticeable/measurable direct effect on crop quality. There was a perception that the presence of green foliage encouraged a higher slug population at one of the sites in 2015-16, but this was not seen in the 2016-17.

The more translucent nature may also have contributed to a 'greenhouse' effect contributing to the relative higher increase in incoming U-value compared to the other treatments.

Given the need for storage space and associated handling issues for it to be economic, it is considered that this would not be a practical option for large scale use at the present time. However, it could easily be used as a supplemental layer in the current system if straw is in short supply.

Cellulose-fibre poly sandwich (Treatment E)

This treatment was identified as one of the cheapest and realistic non-straw alternatives in the previous project FV398a (Roberts & Lacey, 2014). It consisted of a 5 cm deep layer of 'fluffed-up' cellulose fibre sandwiched between two layers of polythene. Any residue should break down in the soil in a similar way to straw (except likely to be more rapid due to greater exposed surface area) and it was used at a lower rate (1.75 kg/m^2) than typical straw (5 kg/m^2), so will have less impact on nitrogen availability for the following crop. It ranked slightly behind the straw treatments (B, C, D) in terms of insulation value, but not significantly so, and still provided adequate insulation for the crop at all sites. The intention with this treatment was that the cellulose fibre would remain dry to maximise its insulation value and the predicted U-values were expected to be similar to treatment D. However it generally became very saturated with water (absorbing 400 to 600% of its dry weight) due to ingress of water under the polythene cover, and clearly reducing its intrinsic insulation value. However, this meant that this treatment also provided the greatest thermal mass, and it is possible that this provided most, if not all, of the frost protection. Indeed on occasion when visiting sites it was noted that the top 1 or 2 cm of insulation material was frozen, although the layer below was not and the crop was fine.

One issue with this treatment was that the fibre tended to fall off the smooth surface of the polythene on the shoulders of the beds during application. This meant that insulation was thinner or non-existent towards the edges of the beds, and resulted in occasional frost-damaged roots in the edge rows.

Given that good results were achieved even though the material became saturated, this treatment was modified to become treatment H in year 2, i.e. without the polythene layer below, so that it is more likely to remain locked in place by the carrot foliage.

Concern has been expressed about the possible presence of heavy metals in the material; the supplier provided analyses of the material (required for health and safety requirements when it is used for house insulation) which indicated levels were below the limits of detection of the analytical methods.

Fibre only (Treatment G)

This treatment was examined in the second year, and envisaged as the simplest way to make use of the cellulose-fibre on a commercial field scale. The product was loosely broken up and then blown onto the crop using a petrol leaf blower with a flexible outlet. The rate used (1.75 kg/m^2) was the same as used in the other fibre treatments, and intended to give a 5 cm depth of material. There was concern that the material would not stay in place on the crop without a cover, this proved to be unfounded. The carrot foliage trapped the initial fibres, and there was very little drift off the target bed. In addition, once the surface had been wetted by the first rain or dew following the initial application, the top layer of material formed a crust, and stayed locked in place for the duration of the winter until harvest.

In terms of frost protection, the material was equivalent to the field standard (straw over poly or straw alone) with a comparable outgoing U-value. Most of the winter the product remained quite wet and when temperatures were coldest, a frozen layer developed in the top 1-2 cm. The material is not quite so effective at preventing warm-up in the spring compared to the field standard. This is presumably because the overall mass was lower and therefore the maximum water content was also lower. Measurements in the first year indicated that the fibre can absorb up to 600% of dry weight in water when saturated, but at harvest was down to 27 to 75% depending on site.

Although not quantified, the crowns of the roots from under the fibre had a better visual appearance than roots from the other treatments. We suspect that this may be due to its relative water absorbency, and freedom from micro-organisms.

From the practical perspective, this treatment is the most feasible non-straw alternative, providing equivalent frost protection to conventional straw, requiring less mass, and so less potential for nitrogen lock-up, better visual quality of the roots, and no risk of weed or disease introduction. It is likely that there could be several options for field application, depending on the form delivery, and ease of adaptation of machinery. Different application methods would likely result in subtle differences in the structure of the layer, therefore additional trials would be appropriate to look at the influence of different application methods on performance.

The price of the bagged cellulose fibre material as supplied for the trial (£480 per t) means that the material cost is about 60% more than conventional straw treatment. It was anticipated that this price could be reduced if being supplied in bulk lorry loads direct to the field, unfortunately this is not the case at the current time (2017).

Poly-over-fibre (Treatment H)

This treatment was examined in the second year and was essentially a modification of the poly-fibre sandwich (treatment E) from the first year, modified by removal of the bottom layer of polythene, as it was found that due to the smooth surface of the polythene, the fibre tended to fall off the shoulders of the beds, resulting in an variable depth or absence of insulation material in places. Removing the bottom layer resulted in improved and even coverage. The polythene over the top was intended to (a) keep the material in place, i.e. preventing it blowing away and (b) keep the material drier than in the fibre-only treatment (G), and this was indeed the case.

In terms of frost protection, the material had a slightly higher outgoing U-value than the field standard (straw over poly or straw alone) or fibre-only. This was probably a result of the lower moisture content providing less thermal mass and protection via latent heat. The material is not quite so effective at preventing warm-up in the spring compared to the field standard, with similar incoming U-values to the fibre-only and poly-over-reduced-straw.

Given that that this treatment did not provide any insulation benefit compared to the fibre-only, and that the fibre-only stayed in place without a cover, there is no justification for the additional cost and extra complication of covering the fibre with polythene.

Black fleece and fleece plus polythene (Treatments X and XP)

These treatments were examined on one site on a speculative basis in 2015-16 only and without detailed temperature records. Significant frost damage occurred in both these treatments, and although this was less than in the uncovered plot, it was unacceptably high and reduced marketable yield. Limited temperature data collected also indicated temperature ranges were almost as great as the uncovered and the mean temperature was higher, neither of which are desirable characteristics. Whilst such a treatment could provide some protection in milder conditions or for short term crops, we suspect that in such situations one or two layers of much cheaper polythene sheet would provide a much more cost-effective solution.

Other possible treatments and future work

The comparative costs of different potential insulation systems for field storage of carrots were presented in the previous project (FV398a; Roberts & Lacey 2014).

Almost any covering over the soil/crop will reduce the rate of heat loss from the soil surface, thereby reducing the risk of frost damage to the crop. It is also clear from this work that whilst having some intrinsic insulation value will be important in an exceptionally dry and cold winter, in most years in the UK much of the frost protection in the current straw systems is derived from the thermal mass and latent heat effects resulting from the significant mass of water retained in the straw.

Thus, whilst growers have generally avoided non-wheat straw and chopped straw, from the insulation and frost protection perspectives, there is no reason why other straws would not be effective (although it is recognised that one of the attractions of wheat straw is that it is easier to remove from beds prior to harvest). It would be useful to have relative insulation values for straws from other crops, thereby allowing growers to prioritise other straw sources when wheat straw is in short supply.

The cellulose-fibre material examined in this project is a processed form of waste paper primarily aimed at the building insulation market, it was fortuitous that it seems to lock itself in place in the field. Other forms of waste paper products may be available locally, and at a lower price e.g. unprocessed shredded paper, wet pulp, paper crumb, it would be valuable to compare such materials in the field to establish not only their relative insulation value, but other characteristics such as their ability to stay in place, the mass/volumes needed etc. There may also be a need to check with the Environment Agency whether a permit is required.

In the first year of the project the cellulose fibre was ‘fluffed-up’ prior to spreading over the crop, in the second year the material was blown into place in the field. It would be useful to have data comparing the impact of different application methods on performance.

Currently about 60% of waste paper is exported from the UK (WRAP UK, 2013). Using some of this material directly in the UK as insulation for carrot crops could be seen as a positive step towards maximising waste recycling locally.

Conclusions

- All of the main treatments provided effective 'insulation' in both years of the trials (2015-16 and 2016-17) at all trial sites.
- The most promising non-straw alternative is a cellulose-fibre insulation product, derived from recycled paper, providing equivalent insulation to current straw systems and for less mass, and resulting in visibly cleaner crowns.
- Although the current straw treatments are inefficient in pure insulation terms, it is likely that a significant part of the frost protection provided results from retention of water in the straw-layer. This provides a greater thermal mass (reducing temperature fluctuations) and reduces freezing due to latent heat of fusion.
- Having a layer of polythene below the straw as well as providing another layer of insulation results in greater water retention in the straw layer, increasing its thermal mass, and increasing the potential for evaporative cooling.
- There is no evidence that light-exclusion by the polythene has any impact on crop quality.
- Covering the straw with a second layer of polythene allows the amount of straw to be reduced by about 2/3.
- Closed-cell PE foam could easily be used as a supplemental layer in the current system if straw is in short supply.

Knowledge and Technology Transfer

Presentation to Carrot and Onion conference November 2015.

Presentation to BCGA technical committee June 2016.

Field open day, Scampston, Yorkshire, February 2017.

Poster at Carrot and Onion conference, November 2017.

Telephone discussions with growers, September-November 2017.

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