Project title:	Practical evaluation of carrot field storage alternatives
Project number:	FV 398b
Project leader:	Dr S J Roberts, Plant Health Solutions Ltd
Report:	Annual Report
Previous report:	None
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
Date project commenced:	01 Aug 2015
Date project completion due:	30 Sep 2017

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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
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 winter of 2015-16.

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 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, and the potential for introduction of problems weed seeds with the straw. 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, supplies of straw are likely to become both more expensive and erratic in future years. 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 reduced quantities of straw or non-straw alternatives. A previous project, (FV398a; Roberts, S.J. & Lacey, T 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 insulations 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, therefore this project aims to:

(a) practical validation of the theoretical insulative values for alternative materials and their impact on crop quality;

(b) to begin investigations of practical implementation of alternative systems..

Summary

Field trials were established in commercial strawed crops of cv. Nairobi. Six treatments (untreated control plus five others) (Table 1, Fig 1) were examined at three different locations (Norfolk, Scotland and Yorkshire) and with two harvest dates. Each plot was 7 or 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. In addition, two speculative, non-replicated treatments were also included at the Yorkshire site.

Table 1. Treatment codes and details.

Code	**Treatment**	**Details/Notes**
A	Uncovered control	Untreated control.
B	Straw alone	Standard covering of straw (commercial standard).
C	Straw over polythene	Straw with a single layer of black polythene below (commercial standard)
D	Reduced straw polythene sandwich	Reduced (approx 1/3rd, ~1.5 kg/m^2) amount of straw with layer of black polythene below and layer of black polythene over the top.
E	Cellulose fibre polythene sandwich	Cellulose fibre, approx 5cm depth, 1.75kg/m^2 with a layer of black polythene below and a layer of white polythene over the top.
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.

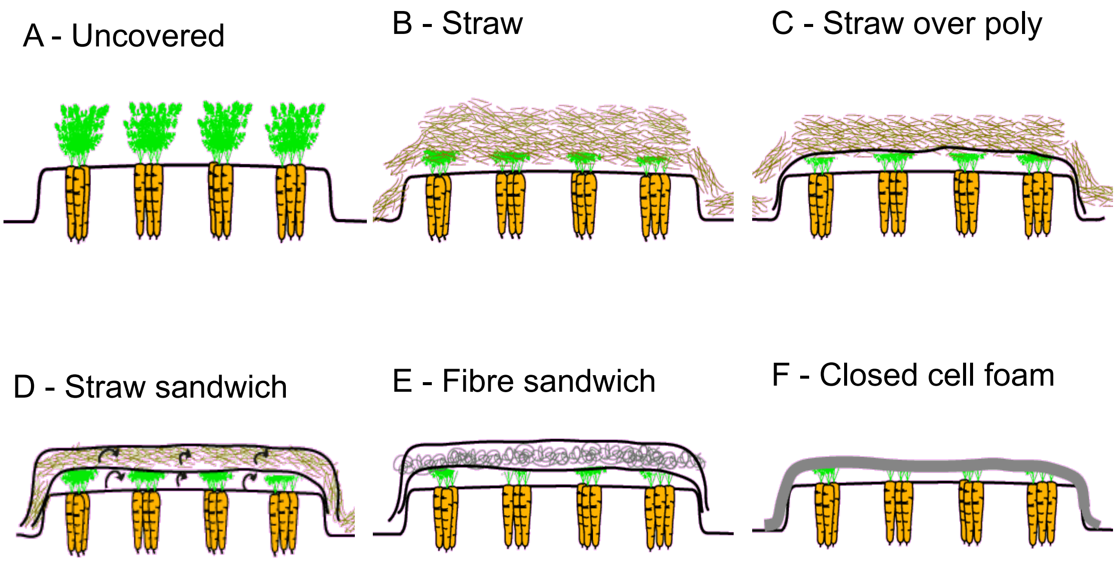

Figure 1. Diagram demonstrating each of the treatments.

All of the treatments provided effective frost protection in the winter of 2015-16, although this was generally a mild winter. The only significant frost damage occurred in the uncovered control (A) and in additional fleece-covered plots at the Yorkshire site. The levels of total damage (frost-damage and crown-rots) are shown in in Fig 2. The average and range of temperatures for each site and treatment are shown in Fig 3. and the average U-values (measures of insulation value) are shown in in Fig 4 for both heat loss and heat gain by the soil.

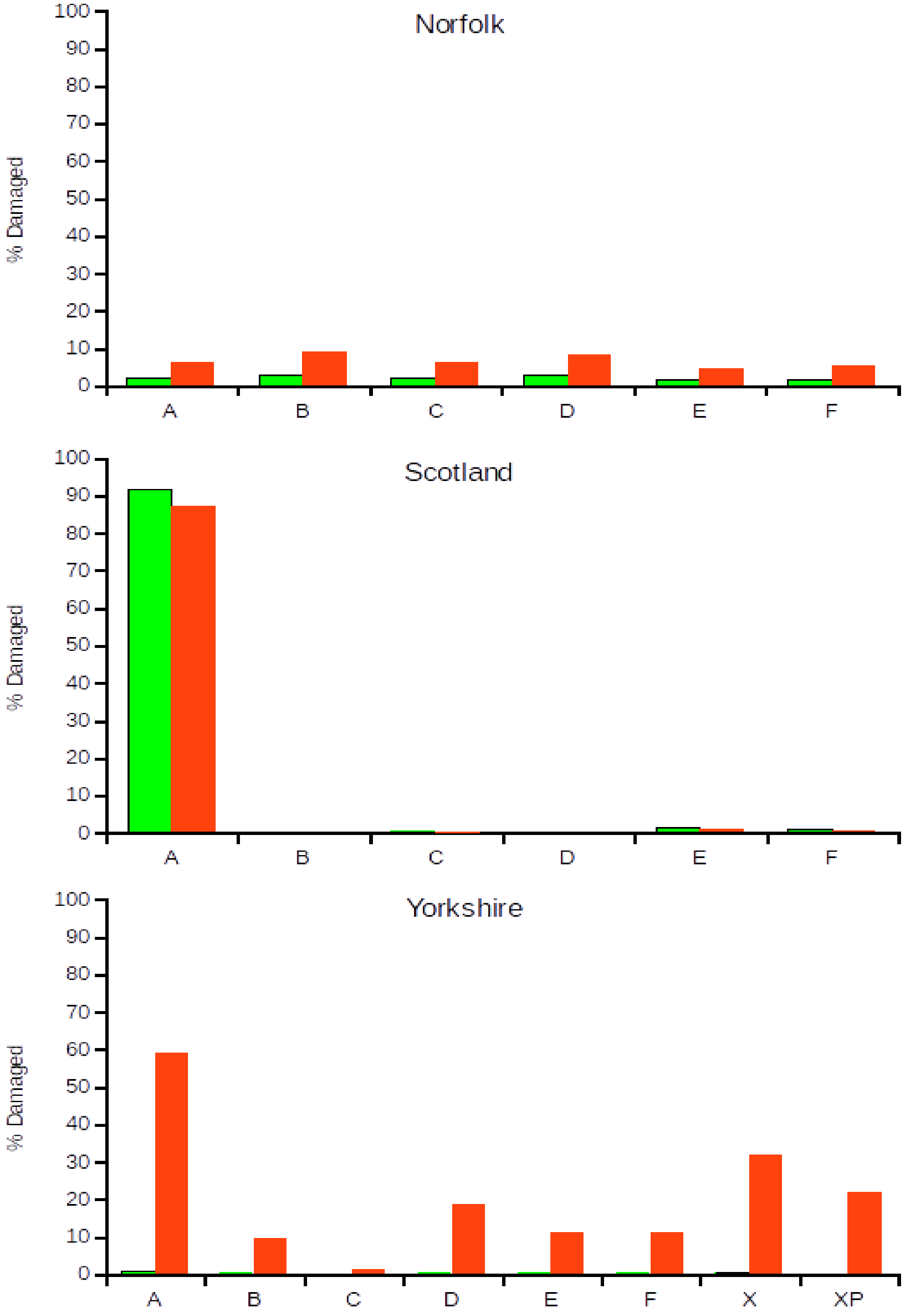

Figure 2. The percentage of damaged carrot roots at each harvest in each treatment at each site. Green (left hand) bars represent the first harvest, red (right hand) bars represent the second harvest.

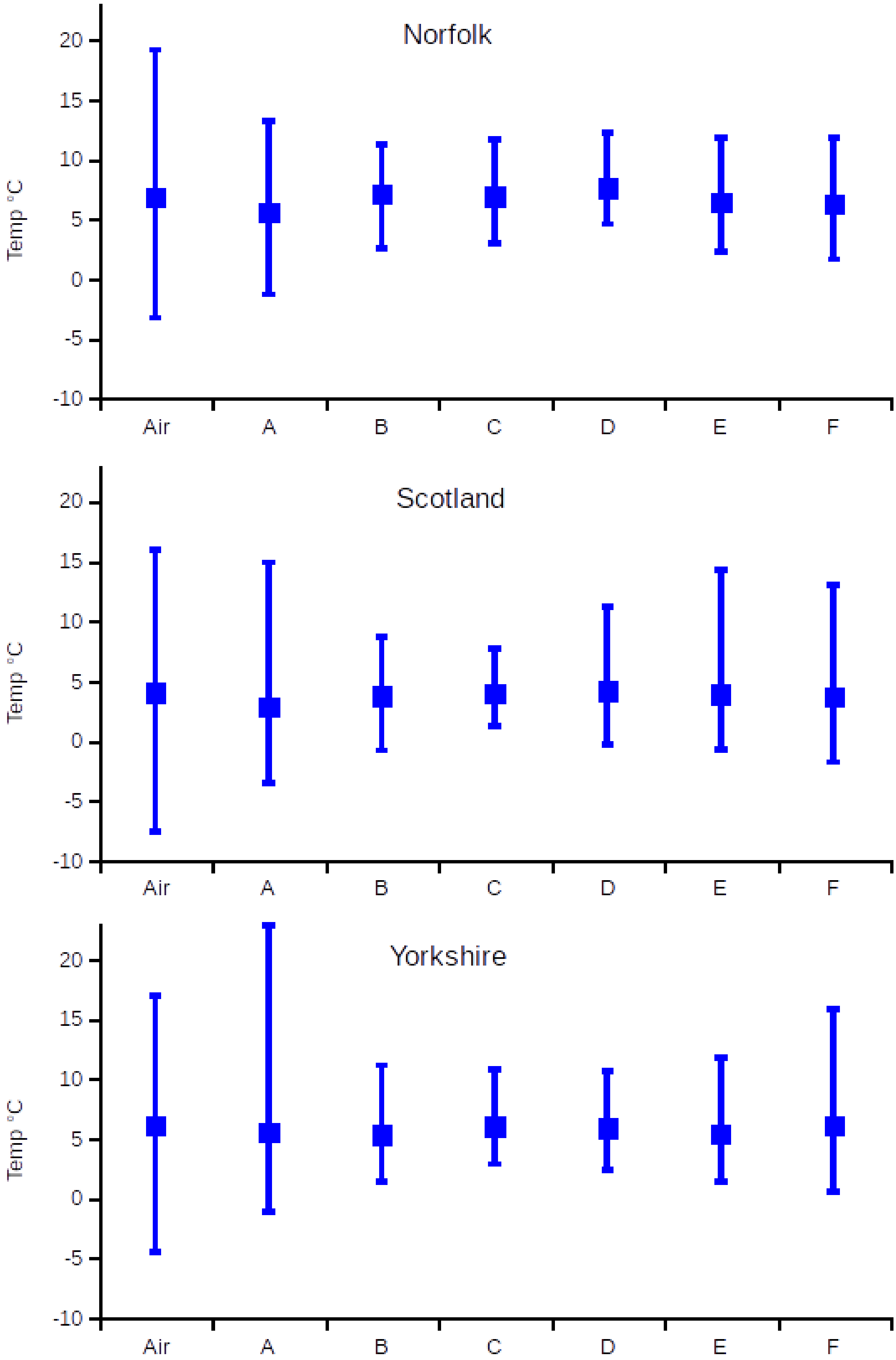

Figure 3. The effect of treatment on the soil surface temperature at each site. The square symbol represents the average, the bars represent the maxima and minima. Air temperature is also shown on the left for reference.

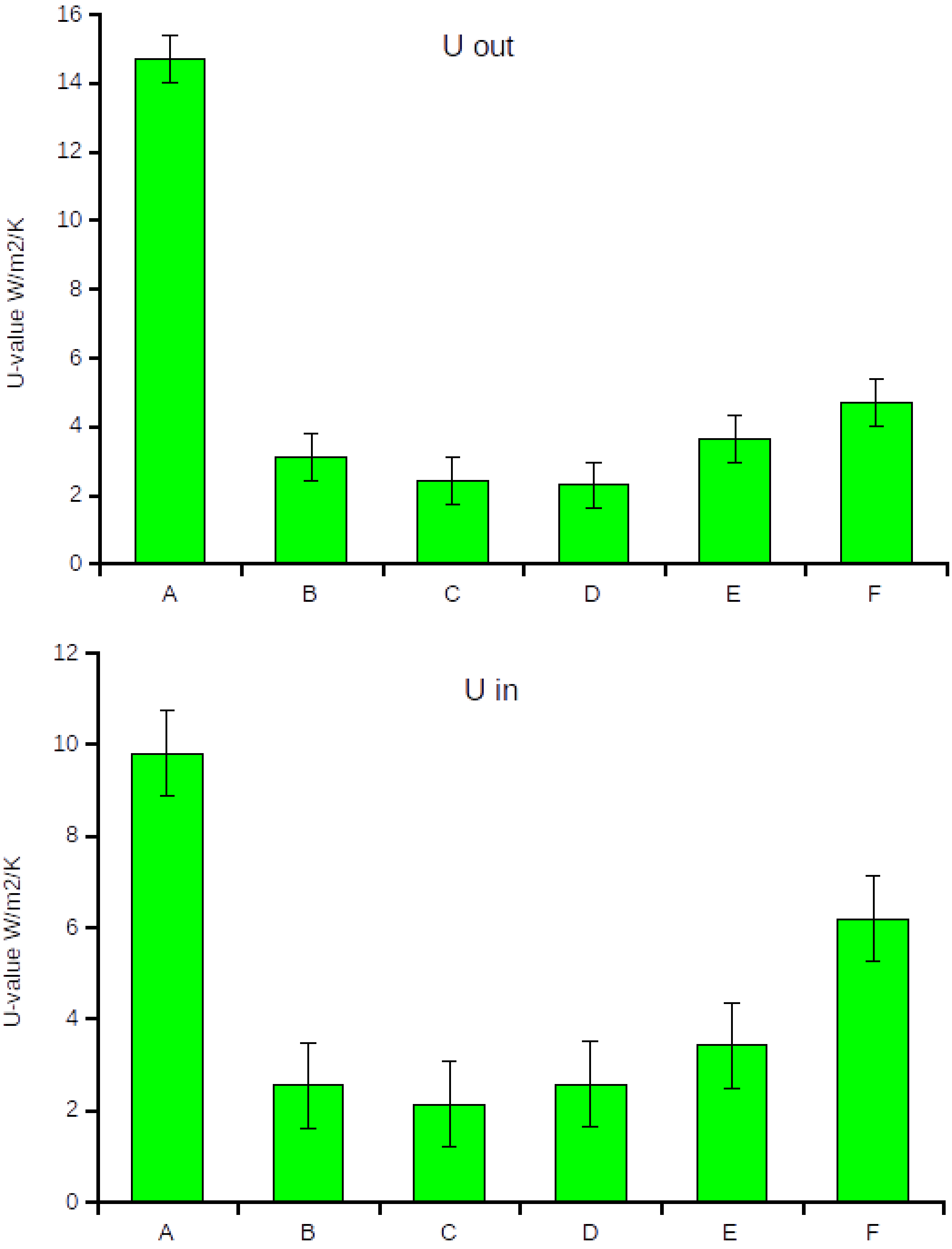

Figure 4. The effect of treatment on the estimated outgoing (soil losing heat) and incoming (soil gaining heat) U-values. A low U-value indicates a good insulator.

Some notes and comments on each of the treatments are given below:

Treatment B (straw alone)

This treatment was included as a commercial standard and to obtain baseline data for current practice. This treatment provided slightly less insulation than treatment C. The straw remains wet at the bottom (but not as wet as treatment C). This has two effects: providing a thermal mass effect (dampening of temperature fluctuations, and the water in the straw will freeze before before the soil/crop) and providing potential for evaporative cooling. We suspect that the thermal mass effect may be an important aspect of the protection provided. The soil in the beds was wetter in this treatment than the others which all had a covering of polythene.

Treatment C (straw-over-poly)

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. The introduction of a polythene layer provides additional insulation. The presence of the polythene also means that the straw remains much wetter than treatment B (about twice the moisture content), often with free water on the surface of the polythene. 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 protecting 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 (FV398a) growers often reported that the main benefit of the polythene under straw was light-exclusion to prevent re-growth. There is 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. It is likely 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.

Treatment D (reduced straw poly sandwich)

This treatment 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 2/3rds by puttying the straw in a polythene sandwich. These results 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 slightly behind treatment C for incoming insulation value.

Treatment E (cellulose-fibre poly sandwich)

This treatment was identified as one of the the cheapest and realistic non-straw alternatives in the previous project (FV398a). It consisted of a 5cm deep layer of 'fluffed-up' cellulose fibre sandwiched between two layers of polythene. Any residue will 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 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 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.

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

Treatment F (closed-cell foam)

This treatment was included as a non-straw alternative and 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, and we were able to recover it intact for re-use at all sites.

One aspect of this treatment not anticipated was that both it and the 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.

Treatment X and XP (black fleece and fleece plus polythene)

Two additional treatments were also examined at the Yorkshire site (i.e. without replication) on a speculative basis without the detailed temperature records. These treatments consisted of a black thermal fleece alone (X) or with an additional cover of black polythene (XP). 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. Whilst such a treatment may provide some protection in milder conditions or for short term crops, but we suspect that one or two layers of much cheaper polythene sheet would provide a much more cost-effective solution.

Conclusions

- All treatments provided effective 'insulation' in the year 2015-16.
- Although the current straw treatments are inefficient in pure insulation terms, it is possible 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 a second layer of polythene allows the amount of straw to be reduced by about 2/3rds, 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.

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 2/3rds could be achievable by using a poly-straw-poly sandwich 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

- Growers wishing to reduce straw usage could consider moving to a poly-straw-sandwich using 1/3rd the normal amount of straw.

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 – 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. 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, supplies of straw are likely to become both more expensive and erratic in future years. 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 reduced quantities of straw or non-straw alternatives. A previous project, (FV398a; Roberts, S.J. & Lacey, T 2014), primarily a theoretical desk-based study, investigated:

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Materials and methods

Treatments

Following discussion with the grower representative and HDC technical manager, six treatments were agreed for the trial:

Table 2. Treatment codes and details.

Code	Treatment	Details/Notes
A	Uncovered control	Untreated control.
B	Straw alone	Standard covering of straw (commercial standard).
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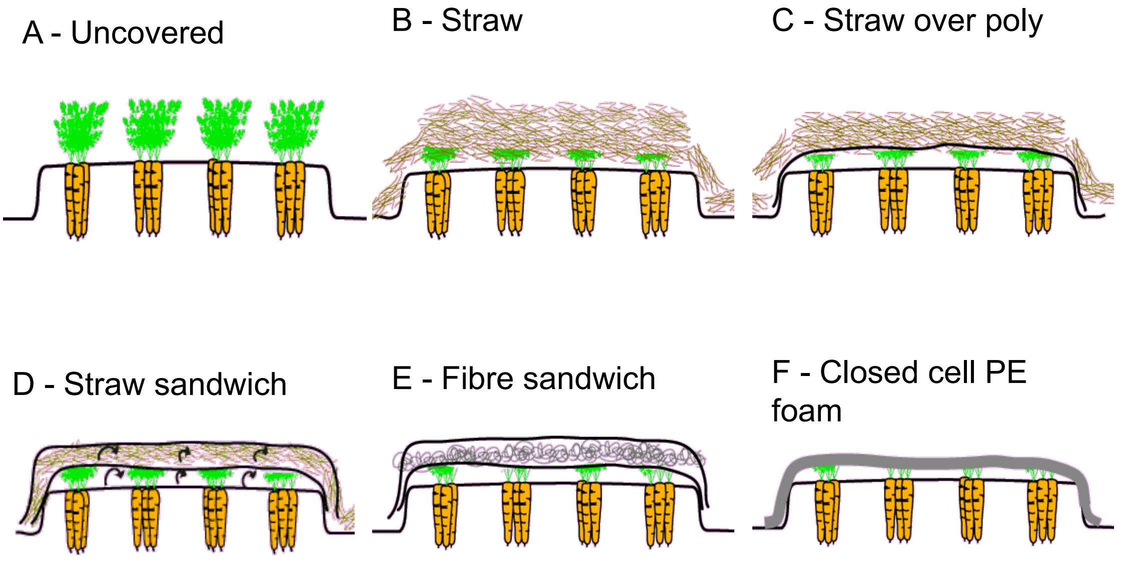

Figure 5. Diagram demonstrating each of the treatments.

Trial sites and layout

Three trial sites in different parts of the UK were selected: Norfolk (North Walsham), Yorkshire (West Knapton), Scotland (Inverurie, Aberdeenshire). Trial crops were selected on the basis that they were designated for the longest term storage to maximise the potential information obtainable.

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 and divided into six plots of seven or eight beds wide by 10m long, arranged as three plots long by two plots wide. Treatments were assigned to plots using a randomised block design, with blocks representing each site.

Straw was carefully cleared by hand from five plots (leaving the field standard at the site intact) and replaced with the appropriate materials after installing temperature and moisture sensors in each plot.

At two sites the field standard was straw over poly (treatment C), and at one site the field standard was straw alone (treatment B). Therefore, depending on the existing treatment the other was implement by removing the polythene from underneath the straw and replacing the straw or by placing a layer of polythene and then replacing the straw. 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.

For treatment D, the cleared bed was covered with a layer of black polythene; dry straw was weighed into large woven sacks and then spread on an appropriate length of bed (3kg per m of bed) to ensure consistent application rate between sites. The straw was then covered with another layer of black polythene.

For treatment E, the cellulose fibre was delivered in 14kg 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 as a layer of white polythene was immediately un-rolled over the top.

For treatment F, the foam and polythene cover was 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 1.1 m intervals.

Sensors and data records

A 60 cm Aquacheck (AquaCheck (Pty) Ltd, South Africa) sub-surface combined soil-moisture and temperature probe was installed 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. 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 one site, Scotland, the soil depth was too shallow to fully insert the probes, so that they were inserted so that the second sensor was 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.

In addition at two of the three sites, an additional set of temperature sensors 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 early February, and the second just prior to the main field harvest by the grower (see Table.)

In each case the insulation was opened up around the 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 and adequate number of roots was assessed). Carrots from the outer two rows were harvested separately from carrots in the inner two 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 and 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 for sugar and dry matter analysis.

Data handling and analysis

Harvest data

The numbers of frost-damaged and crown-rotted roots was 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. Yield and marketable yield were subject to analysis of variance using Genstat (Payne *et al.* 2005).

Temperature data

A total of around 600K data records were accumulated from the various sensors. 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 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:

$$qa = C_v \times (\Delta T_1 + \Delta T_2)/2 \times (z_1 - z_2)$$

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 as:

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

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

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

where *AT* and ST_0 are the air temperature (measured at approximately 60cm above the soil surface) and temperature at the soil surface.

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
Norfolk (N. Walsham)	29/05/15	Nairobi	10/11/15	11/02/16	29/02/16
Scotland (nr. Inverurie, Aberdeenshire)	18/05/15	Nairobi	20/11/15	10/02/16	04/05/16
Yorkshire (W. Knapton)	05/03/15	Nairobi	25/11/15	11/02/16	27/04/16

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. Results are shown in figure 6. 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 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)

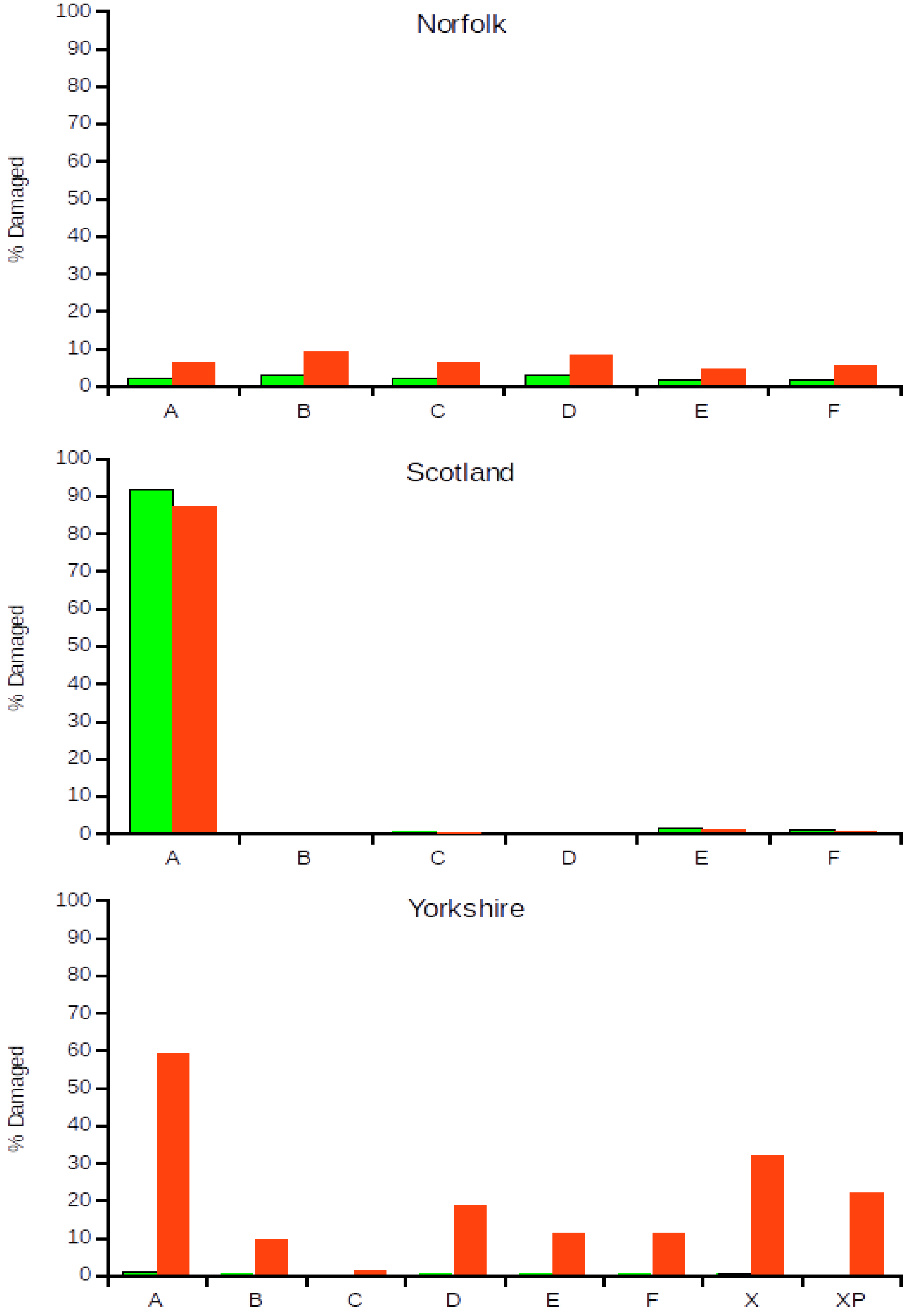

Figure 6. The percentage of damaged carrot roots at each harvest in each treatment at each site. Green (left hand) bars represent the first harvest, red (right hand) bars represent the second harvest.

Cavity spot

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.

Yield

The marketable yields for each treatment and site are show in Fig 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 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.

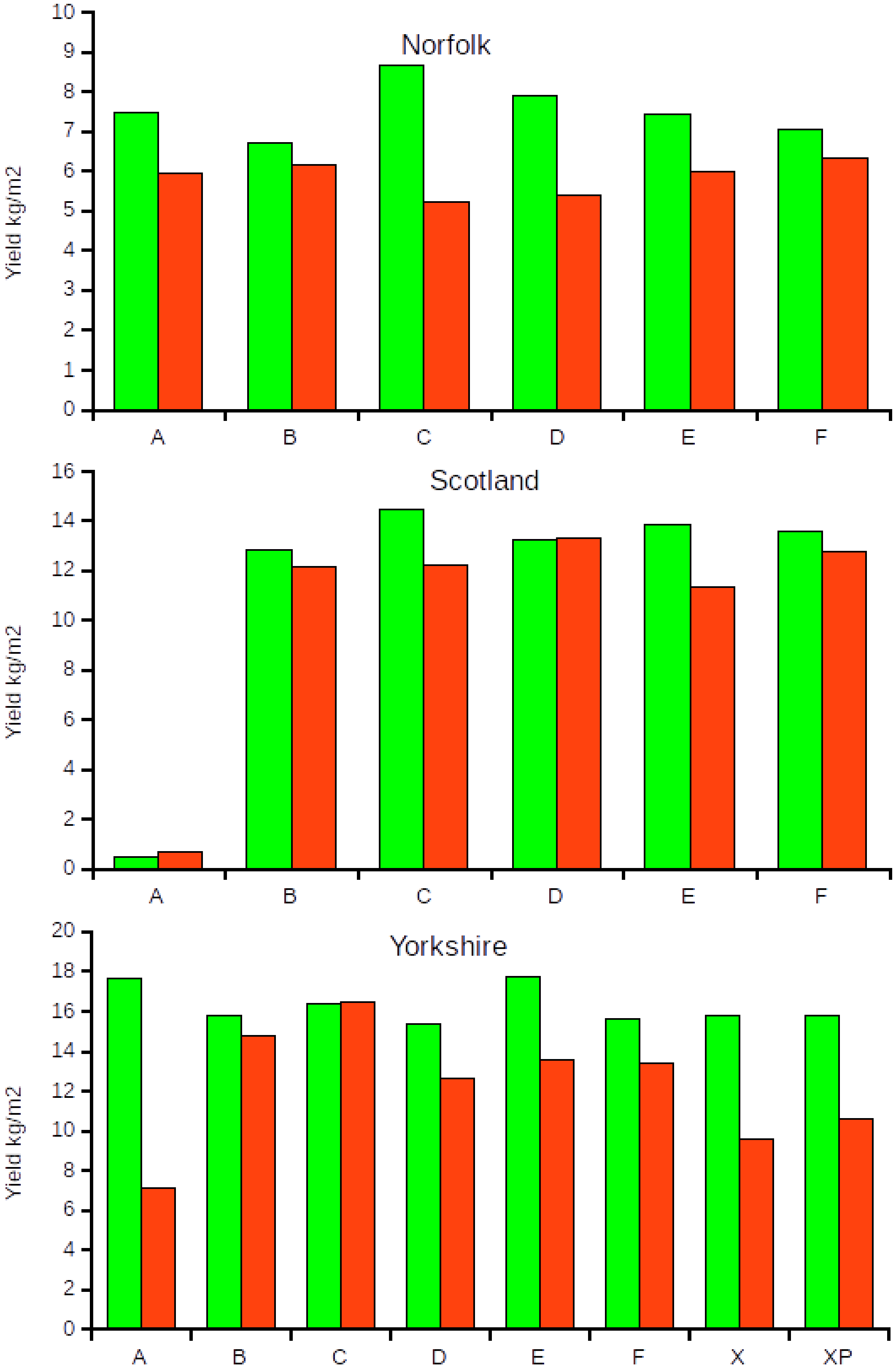

Figure 7. Effect of treatments on the marketable yield for each harvest data and site. Green (left hand bars) represent the first harvest, red (right hand bars) represent the second harvest.

Sugars and dry matter

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

Soil Moisture

Overall average absolute soil moisture values varied between plots (treatments) within each site, but there were no consistent treatment effects, and it is likely that in most cases this was more 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) and 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.

Temperature

The mean, min, max and mean soil surface temperatures and air temperatures at each site are shown in Fig. 8. The lowest soil surface temperature recorded was -3.6°C in the uncovered plot in Scotland, 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° for the standard screened air temperature at a height of ~60cm 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.

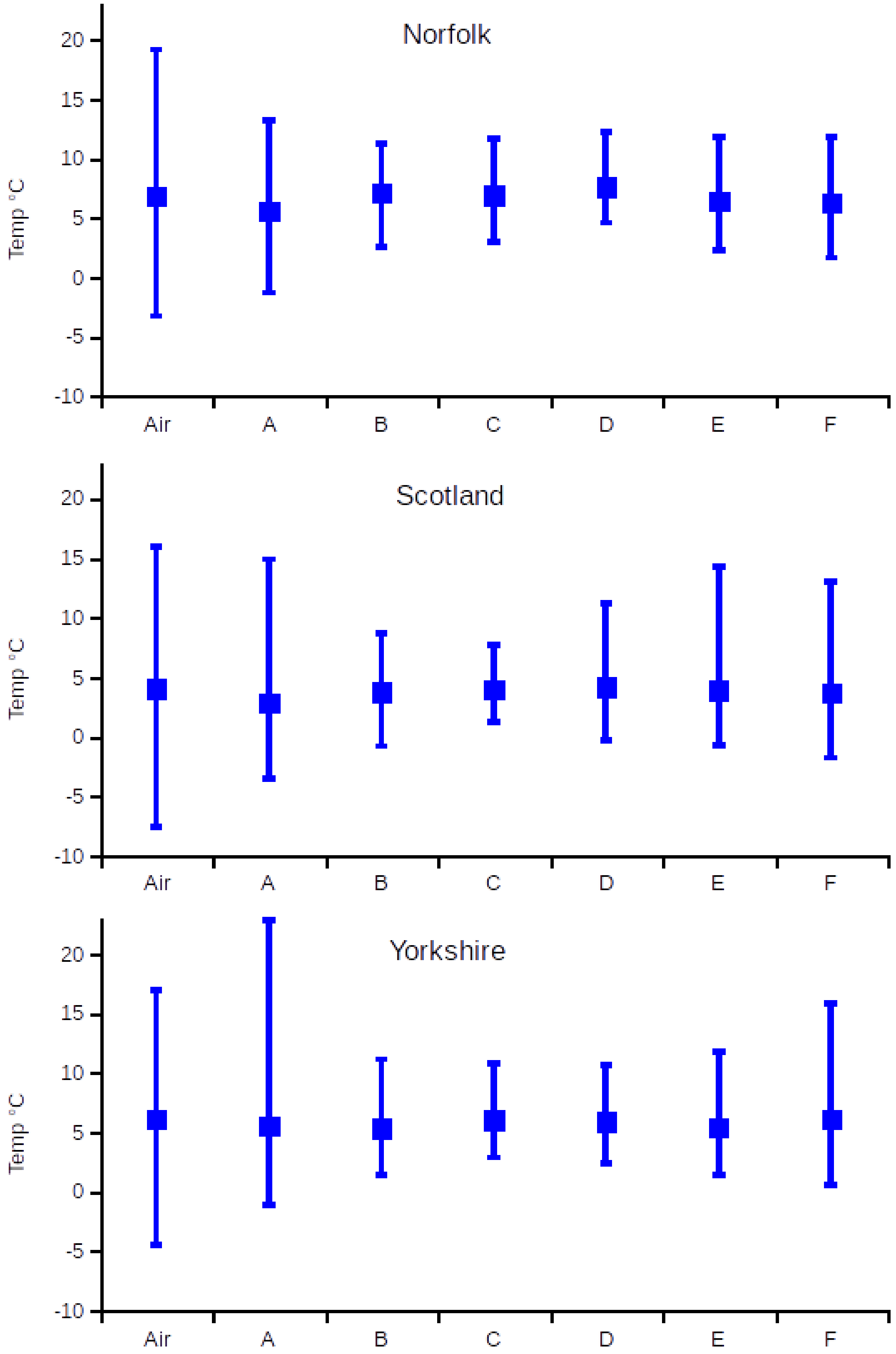

Figure 8. The effect of treatment on the soil surface temperature at each site. The square symbol represents the average, the bars represent the maxima and minima. Air temperature is also shown on the left for reference.

Insulation value

U-values in Watts per m^2 per K (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 was positive. Values were calculated separately for heat loss and heat gain by the soil and are summarised in Fig 9.

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.

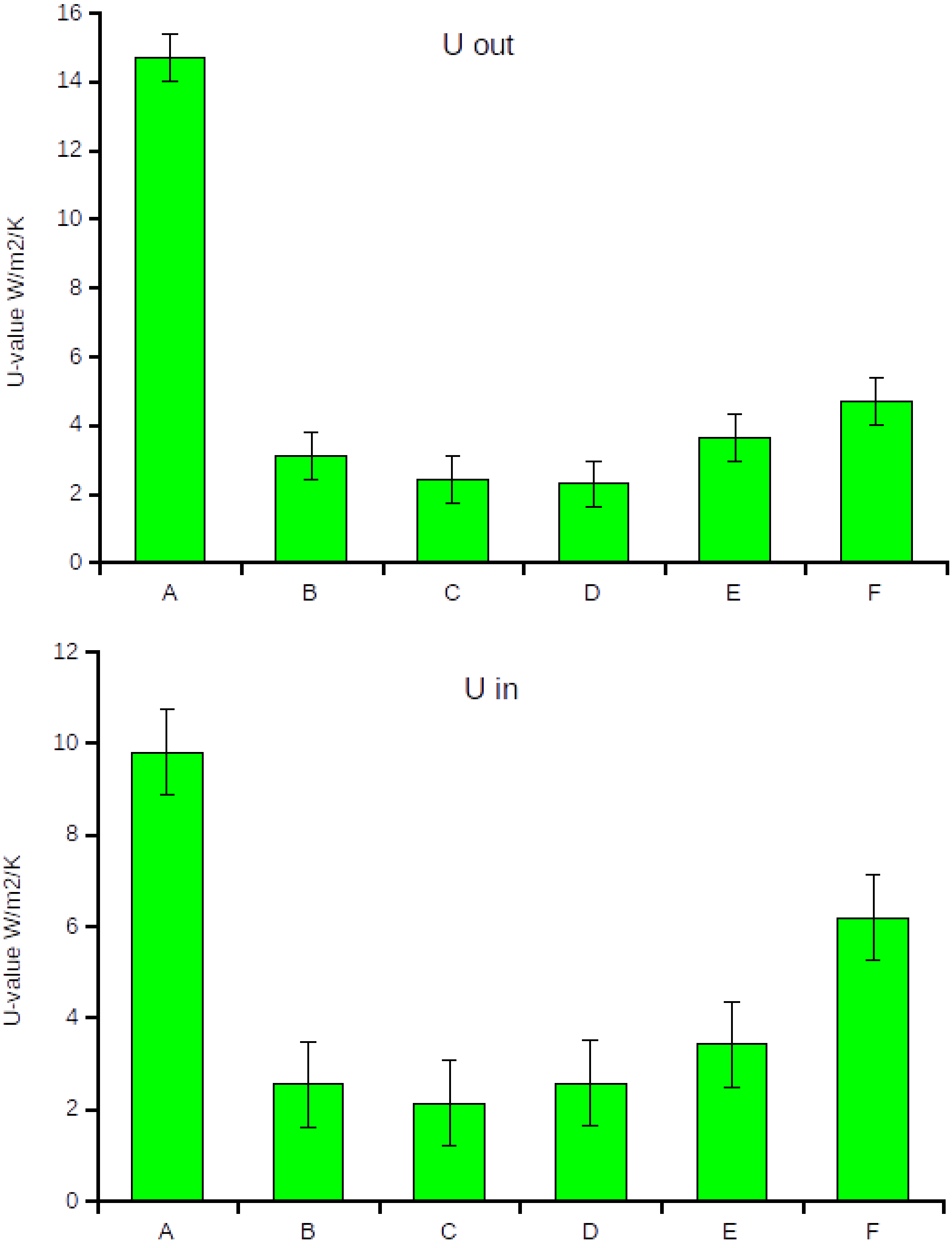

Figure 9. The effect of treatment on the estimated outgoing (soil losing heat) and incoming (soil gaining heat) U-values. A low U-value indicates a good insulator.

Discussion

All of the main treatments provided effective insulation compared to the uncovered control and were effective in eliminating significant frost damage at all three sites during the winter

2015-16. This was reflected in the yield and proportions of damaged roots at each site, the minimum soil-surface temperatures recorded at each site and the calculated (outgoing and incoming) U-values. However it should be noted, that 2015-16 was a relatively mild winter, and so it might be expect that the treatments might be more challenged in more severe winters.

The theoretical basis for measuring and comparing insulation values are presented in the previous project (FV39a; Roberts, S.J. & Lacey, T 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 could feasibly 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). 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 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.). 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: D, C, B, E, F. These were more or less in line with the expected rankings based on theoretical values, except for treatment E (see note on each treatment later). The in-coming (i.e. when heat was being gained by the soil) U-values were ranked in a slightly different order: C, B, D, E, F. It would be expected that in-coming and out-going would rank similarly, but we suspect that this may be due thermal mass effects and evaporative cooling.

Some notes and comments on each of the treatments are given below:

Treatment B (straw alone)

This treatment was included as a commercial standard and obtain baseline data for current practice. 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 treatment C. The straw remains wet at the bottom (but not as wet as treatment C). This has two effects: providing a thermal mass effect (dampening of temperature fluctuations, and the water in the straw will freeze before before the soil/crop) and evaporative cooling. We suspect that the thermal mass effect may be an important aspect of the protection provided. The soil in the beds was wetter in this treatment than the others which all had a covering of polythene.

Treatment C (straw-over-poly)

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. 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 provided slightly greater insulation than treatment C. The presence of the polythene also meant that the straw remains much wetter than treatment B (about twice the moisture content), and often with free water on the surface of the polythene. Again it seems likely that 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 protecting 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 (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 therefore suspect 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.

Treatment D (reduced straw poly sandwich)

This treatment 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 2/3rds 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 slightly behind 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. It may therefore be worth investigating whether a similar result can be achieved with reduced straw by omitting the bottom layer of polythene, and using a thinner layer of straw on top to provide anchorage, i.e. straw-poly-straw instead of poly-straw-poly.

Treatment E (cellulose-fibre poly sandwich)

This treatment was identified as one of the the cheapest and realistic non-straw alternatives in the previous project (FV398a; Roberts, S.J. & Lacey, T 2014). It consisted of a 5cm 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 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 even we achieved good results even though the material became saturated, it would be worth examining the use of cellulose-fibre 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 EC health and safety requirements when it is used for house insulation) which indicated levels were below the limits of detection of the analytical methods.

Treatment F (closed-cell foam)

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, and we were able to recover it intact for re-use at all sites.

One aspect of this treatment not anticipated was that both it and the 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.

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.

Treatment X and XP (black fleece and fleece plus polythene)

At the Yorkshire site (i.e. without replication) two additional treatments were also examined on a speculative basis without the detailed temperature records. These treatments consisted of a black thermal fleece alone (X) or with an additional cover of black polythene (XP). 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 may provide some protection in milder conditions or for short term crops, but we suspect that in such situations a one or two layers of much cheaper polythene sheet would provide a much more cost-effective solution.

Conclusions

- All treatments provided effective 'insulation' in the year 2015-16.
- Although the current straw treatments are inefficient in pure insulation terms, it is possible 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 2/3rds.
- The two non-straw alternatives: cellulose fibre and closed-cell PE foam both provide 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.

Knowledge and Technology Transfer

Presentation to Carrot and Onion conference November 2015.

Presentation to BCGA technical committee June 2016.

References

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