Outline

- UK System
- Characteristics of current system
  - Trying to understand what is happening
- Possible alternatives
  - Theory
  - Field trials

Typical UK system

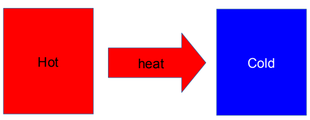
- **Winter storage in the field**
  - All carrot types: Nairobi, Chantenay
  - Best quality crops selected
  - 3 or 4 double or triple rows per bed (1.8 or 2 m)
- **End October and November**
  - Covered with straw or straw over black polythene
  - 80-90 'Heston' bales (1.2 x 1.2 x 2.4m) per ha (40 to 50 t/ha)
  - ~30 cm depth of straw
- **Problems / Concerns**
  - Availability, and price of straw
  - Weed seeds, especially black-grass (*Alopecurus myosuroides*)
  - Nitrogen 'lock-up' – less nitrogen available for following crop as straw decomposes
- **Interest in developing alternatives...**

What are we aiming for ?

- **Base temperature for carrot growth ~1°C**
  - Ideal storage temp 0-2°C
- **During winter**
  - Prevent freezing
  - Freezing point of both soil and carrots will be below 0°C (depression of freezing point by solutes)
- **During spring**
  - Keep as cool as possible
  - Prevent/reduce re-growth
- **Keep costs down**
- **Minimise environmental impact**

Now the physics part…

- **First law of thermodynamics**
  - Conservation of energy
  - Energy can transferred from one form/state to another but cannot be created or destroyed
- **Second law of thermodynamics**
  - Heat will flow from a hotter body to a colder body

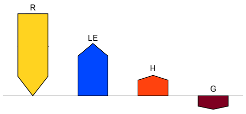


Thermodynamics

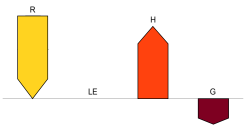
- **Frost doesn't penetrate**
- **Heat is lost from the soil surface**

Soil surface energy balances

Day, moist surface



Day, dry surface

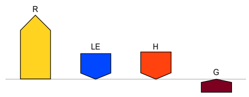


R = Net radiation (in minus out)
LE = latent heat (evaporation)
H = Sensible heat (air movement, conduction
G = Soil heat flux (conduction)

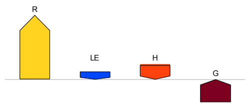
R + H + LE + G = 0

Soil surface energy balances

Night, moist air



Night, dry air



R = Net radiation (in minus out)
LE = latent heat (condensation)
H = Sensible heat (air movement, conduction)
G = Soil heat flux (conduction)

R + H + LE + G = 0

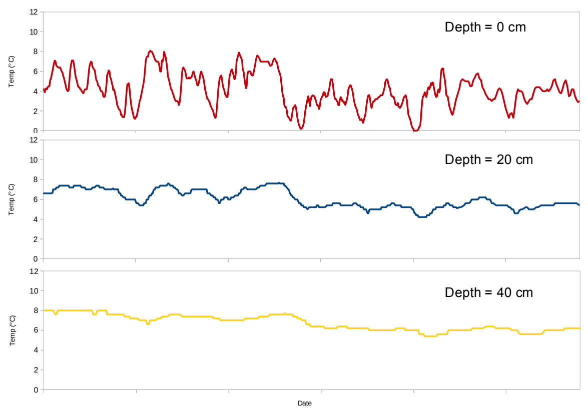
Characterising current system

- **It's complicated !**
- **Mass heat (energy) transfer**
  - In the soil
  - In the insulation layer
  - Between surface and atmosphere
- **Need to understand different heat transfer methods**
  - radiation, conduction, convection, latent heat
- **Principles well understood for soil/plant/air**
- **Lot of info. / theory of insulation from buildings**
- **Very little info. for layers of straw !**

It's complicated !

- **More complex and dynamic than first imagined**
- **Lots of over-simplification...**
- **Soil**
  - below about 1 m v. little temp variation
  - net energy gain in the day/summer, net loss at night/winter
  - soil type and soil moisture affect k (conductivity) and D (diffusivity) values
  - conductivity: sand > clay > peat; moist > dry
  - ground is a big reservoir of heat energy (cf. ground source heat pumps)
  - to stop surface temperature dropping/freezing at night/cold days....
    - need to transfer heat upwards at the same rate as being lost …
    - and/or reduce heat loss with a layer of insulation....

Soil temperature/depth – Carrots Nov 2013



Important insulation terms

- **k-value (intrinsic property of a material)**
  - thermal conductivity, W/m.K
  - low → good insulator
- **R-value (accounts for k and thickness)**
  - thermal resistance, m^2K/W
  - takes account of thickness = l/k
  - high → good insulator
- **U-value (used for a system as a whole)**
  - thermal transmittance, W/m^2K
  - $1/(R_1 + R_2 + R_3)$, combines R values for all components
  - low → good insulator
- **D**
  - thermal diffusivity
  - ratio of thermal conductivity, k, to volumetric heat capacity, c
  - determines speed of temperature change

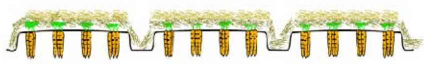
Typical insulation values

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

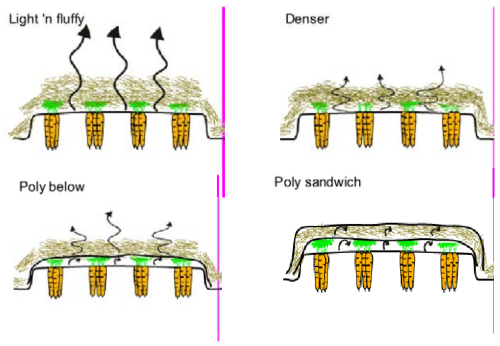
Low k = good insulator
Still air is a very good insulator
Many insulation materials work by trapping pockets of still air:
- air pockets must be small to prevent convection ;
- must be no continuous air gaps (cf. draft proofing);

Straw insulation

- **Current system is very inefficient**
  - but it works ! (Mostly ?)
  - might be a good thing ? !
- **k-values are variable**
  - open surface layer → more heat loss, affected by wind speed
  - moist/wet → conduction, latent heat
  - low density → continuum of air space



Straw convection



Straw and moisture

- **Moisture content of straw layer: ~250% w/w**
- **All insulation values in the literature based on dry straw**
- **Moisture will increase conductivity (reduce insulation value)**
- **Also increases thermal mass (stored heat)**
- **Evaporative conditions → increased heat loss**
  - cooling benefit in the spring ?
- **Freezing conditions:**
  - initially may reduce rate of downward movement of ~0°C isotherm
    - water has to freeze in each layer first
    - latent heat of fusion (334 kJ/kg) >> specific heat capacity (4.2 kJ/kg.K)
  - but once frozen ice is a better conductor than water (~4X)
- **Is it better to maximise insulation by keeping dry?**

Polythene (below straw)

- **Light exclusion ?**
  - No evidence or research on effects of light on storage/re-growth.
  - Temperature is main driver of re-growth.
  - May affect physiology, plant hormone levels ?
- **Little intrinsic insulation value BUT...**
  - traps an air layer, prevents evaporation
  - provides surface resistance to heat transfer
  - cf. survival bags work !
- **Potentially equivalent to about 3-5 cm of *dry* straw.**
- **Effects on gas exchange: $CO_2\uparrow$ $O_2\downarrow$?**

Thermal bridging

- Heat moves horizontally as well as vertically
- Follows the path of of least resistance
- Wheelings comprise approx 16% of field area – significant heat loss
- Straw filling in the wheelings is a good thing

Straw alternatives

- **Based on comparison of insulation values**
- **Using realistic k-values for straw**
- **Compare systems using U-value (low = good)**
- **Ideal requirements:**
  - equivalent/better insulation than current systems
  - no more expensive than current system
  - bio-degradable or re-useable
  - similar or lower transport costs (lower bulk)
  - can be laid as quickly, with similar labour to current
- **Ideal insulation would give a continuous cover with no gaps (thermal bridges)**
  - but where would the water go ?

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Reduced straw

System	Bales	Depth	Densit	Moist	k	R1	R2	U	£/m2
Dry straw	90	15.5	28.6	0	0.22	0.70		1.42	0.31
Dry + Poly	90	15.5	28.6	0	0.22	0.70	0.15	1.17	0.36
Moist straw	90	15.5	28.6	286	0.31	0.51		1.97	0.31
Moist + Poly	90	15.5	28.6	286	0.31	0.51	0.15	1.52	0.36
Poly top + straw	29	5	28.6	0	0.065	0.77	0.15	1.09	0.15
Foil + straw	29	5	28.6	0	0.065	0.77	0.34	0.90	?

- **Poly on top of straw clear benefit**
  - maximises insulation value of straw
  - potentially only 1/3rd amount of straw needed
  - challenge is to keep poly in place

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Non-straw alternatives

System		Depth	Dens	Moist	k	R1	R2	Ri	Re	U	£/m	
Moist straw	90	15.5	28.6	286	0.31	0.507				1.97	0.31	
SF19		3.8				2.21		0.11	0.033	0.42	5.00	
TLX Gold (breathable)						0.95		0.11	0.033	0.91	1.5?	*
poly-Rockwool-poly		5			0.044	1.14	0.15	0.11	0.033	0.70	2.00	*
2 layers Vattex + poly		0.8	94		0.037	0.22	0.15	0.11	0.033	1.96	2.40	
1 layers Vattex +poly		0.4	94		0.037	0.11	0.15	0.11	0.033	2.49	1.20	
Closed cell PE foam		0.75			0.037	0.20		0.11	0.033	2.89	1.46	*
Closed cell PE foam		2			0.037	0.54		0.11	0.033	1.46	3.68	*
Warmcell poly sandwich		4	40	0	0.044	0.91	0.15	0.11	0.033	0.83	1.10	*
poly-PAS100 GW		5	400		0.06	0.83	0.15			1.02	0.07	200 t/ha !!
Starch peanuts poly sandwi		5			0.04	1.25	0.15	0.11	0.033	0.65	1.72	
Foil/Bubble		0.4				0.12		0.11	0.033	3.75	1.49	
Poly alone		0	0	0	0	0.00	0.15			6.67	0.05	

- All except closed cell PE need to be dry
- Nearly all are much more expensive than current
- Need to be re-used several times to be cost effective
- Biggest challenge - to anchor down/keep in place

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Field trials

- **Two winters: 2015-16 and 2016-17**
- **Validate theoretical calculated U-values etc.**
- **Six treatments each year**
- **Three locations:**
  - Aberdeenshire (Scotland), Yorkshire, Norfolk
- **Two harvest dates**
  - end January, early May
- **Data**
  - Temperature sensors at up 6 depths (0 to 60 cm) in each plot at each location
  - Calculate the heat loss or heat gain each hour and then the relative insulation U-values
- **Large plots to avoid 'edge' effects**
  - 6 to 8 beds x 10 m

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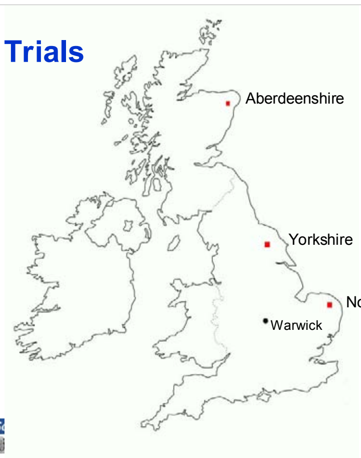
Field Trials



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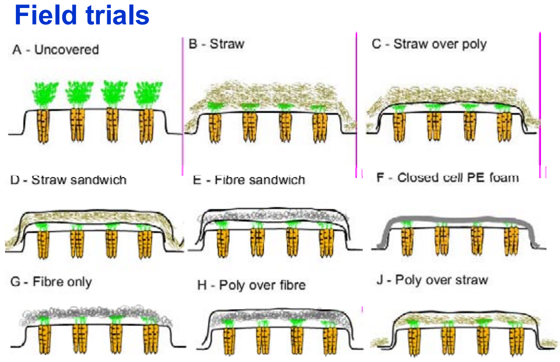
Field trials



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Field trials 2016-17

Site	Covered	Harvest 1	Harvest 2
Norfolk	26/10/16	25/01/17	27/04/17
Aberdeenshire	08/11/16	24/01/17	03/05/17
Yorkshire	26/10/16	25/01/17	26/04/17

Treatments 2016-17

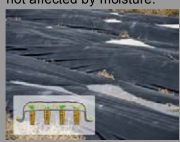

Uncovered control


Field standard. Straw or straw over poly.


Closed cell PE foam. Used in camping mats, insulation not affected by moisture.

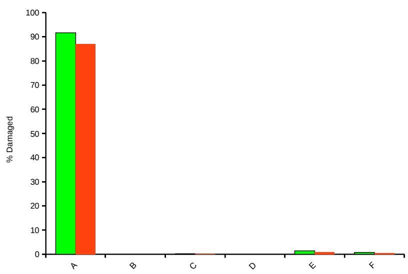

Cellulose fibre. Made from waste paper. Absorbs a lot of water.


Poly over cellulose fibre. Aiming to keep drier and maximise insulation.

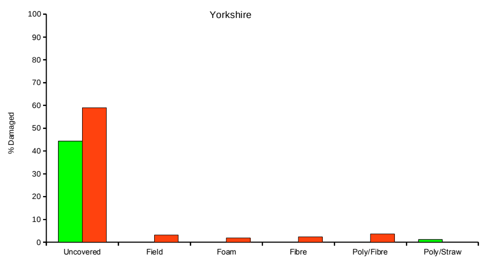

Poly over reduced straw. 1/3rd rate, maximise insulation by trapping air.

Yorkshire 2016-17 final harvest

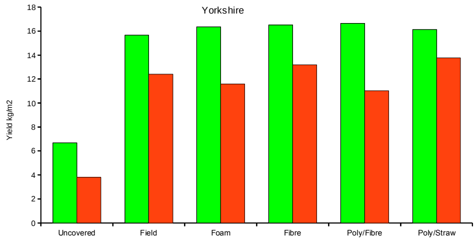
Frost damage 2015-16



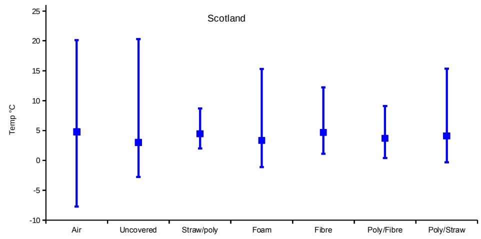
Frost damage 2016-17



Marketable Yield 2016-17



Temperatures 2016-17

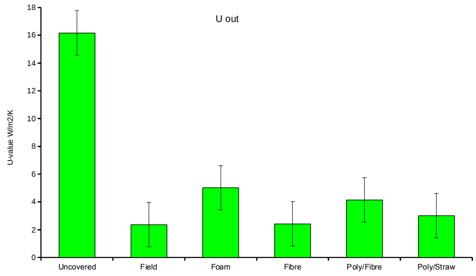


Air temperature and soil surface temperatures, mean and range

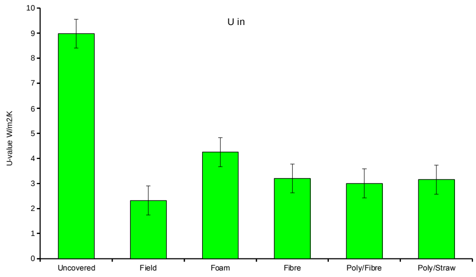
U-values

- U-values are used to compare the insulation value of a 'system'
- Watts per sq. metre per degree, W/m^2/K
- Lower value → better insulation
- Used the hourly temperature and moisture values at each depth in the soil to calculate the heat loss/gain in each layer of soil for each hour, divide by 3600 (seconds in an hour), divide by the temperature difference between the soil surface and the air temp.
- Separate calculations:
  - Heat loss when air temperature is lower than soil temperature
  - Heat gain when air temperature is higher than soil temperature

U-values (heat loss)



U-values (heat gain)



Summary of the 2016-17 treatments

Uncovered

- Included as a negative control
- High levels of frost damage
  - 50 to 90%
- Significant reduction in marketable yield


Straw only

- Inefficient in pure insulation terms
- Bottom layer of straw becomes very wet (~8 kg/m^2)
  - thermal mass effect
  - latent heat of fusion (water in the straw must freeze before the soil / carrots)
  - evaporative cooling


Straw over poly

- Inefficient in pure insulation terms
- Polythene adds insulation
  - equivalent to 3-5 cm of dry straw
- Polythene keeps bottom layer of straw wetter (~14 kg/m^2)
  - greater thermal mass effect = less fluctuation
  - more latent heat of fusion (water in the straw must freeze before the soil / carrots)
  - more evaporative cooling = less regrowth in the spring


Poly over reduced straw

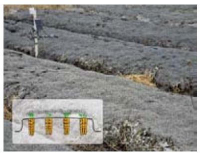
- 1/3rd amount of straw
- Top layer of polythene traps air
- Equivalent insulation to standard straw
- No evaporative cooling in the spring
- An option if straw is in short supply


Closed cell PE foam

- 7.5 mm closed cell polyethylene foam
- Very efficient insulation
- Not affected by moisture
- Expensive but re-usable
- Need to re-use for several years to be cost effective
  - need somewhere to store
- Need to develop system for anchoring in the field
- Allows light through
  - tops stay green, but no effect on quality


Cellulose fibre

- Applied at rate of 17.5 t/ha
  - depth ~5cm
- Forms a crust on the surface
- Can absorb a lot of water (up to 600%)
  - thermal mass effect
  - latent heat of fusion (top 1-2 cm freezes protecting the crop underneath)
- Very clean crowns at harvest
  - relatively sterile
  - draws moisture away from carrot
- Less nitrogen lock-up
- No polythene waste
- Commercial development in progress....




Poly over cellulose fibre

- Aim to keep the fibre dry and maximise insulation value
- Outgoing U-value worse than fibre alone
  - lower moisture
  - less thermal mass
- No performance benefit compared to fibre only
- More cost than fibre only

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Conclusions

- All treatments were effective
  - no significant differences in marketable yield between cover treatments
- Conventional straw treatment inefficient as an insulator
- Straw use can be reduced by 2/3rds by covering with polythene
- Much of the frost protection with straw results from freezing of water in the bottom layer of straw
- Polythene below straw means the straw stays wetter, providing a bigger dampening effect and more evaporative cooling in spring
- Cellulose fibre and similar products could be viable non-straw alternatives
  - less nitrogen lock-up, very clean crown

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Acknowledgements

- Tim Lacey who got the work started at VCS
- AHDB Horticulture and BCGA for financial support
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- The three growers providing us with trial sites:
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  - TBG
  - AA Carrots
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Thank you for listening

Any questions?

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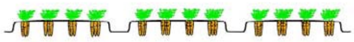

Links to more info: https://planthealth.co.uk/publications

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