Sheep's wool as a carbon sequestration tool:

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Executive summary:

- C from consumed forage or feed is converted into wool by sheep. This conversion is, at most, 50% weight of wool fibre constituting carbon
- There are studies highlighting supplements, genetics, nutrition and management considerations towards increasing wool yields and thus C yields
- If any strategy that increases wool yields requires more carbon input than it derives it is unfeasible – which is likely the case for many strategies other than potentially genetics
- C in wool can't be considered sequestered as sequestration implies that carbon fixed from the atmosphere outweighs the C released to the atmosphere by a system over a period of time
- Wool could be considered an element towards the mitigation of CO_2 equivalent emissions, within the balance of a sheep farming system, but this depends how the system is initially measured and what is ultimately done with the wool
- Even by viewing wool as a by-product, for consideration outside of C balances for animal growth for meat, the C storage value is relatively low (At most negating 2% of the average Welsh emissions associated with sheep meat farming (per fleece/per kg meat)
- Not utilising wool usefully is, however, a direct route to increasing a sheep farms emission profile, as such, the message should be to utilise wool in some way other than burning or disposing of it despite its, currently, low economic value

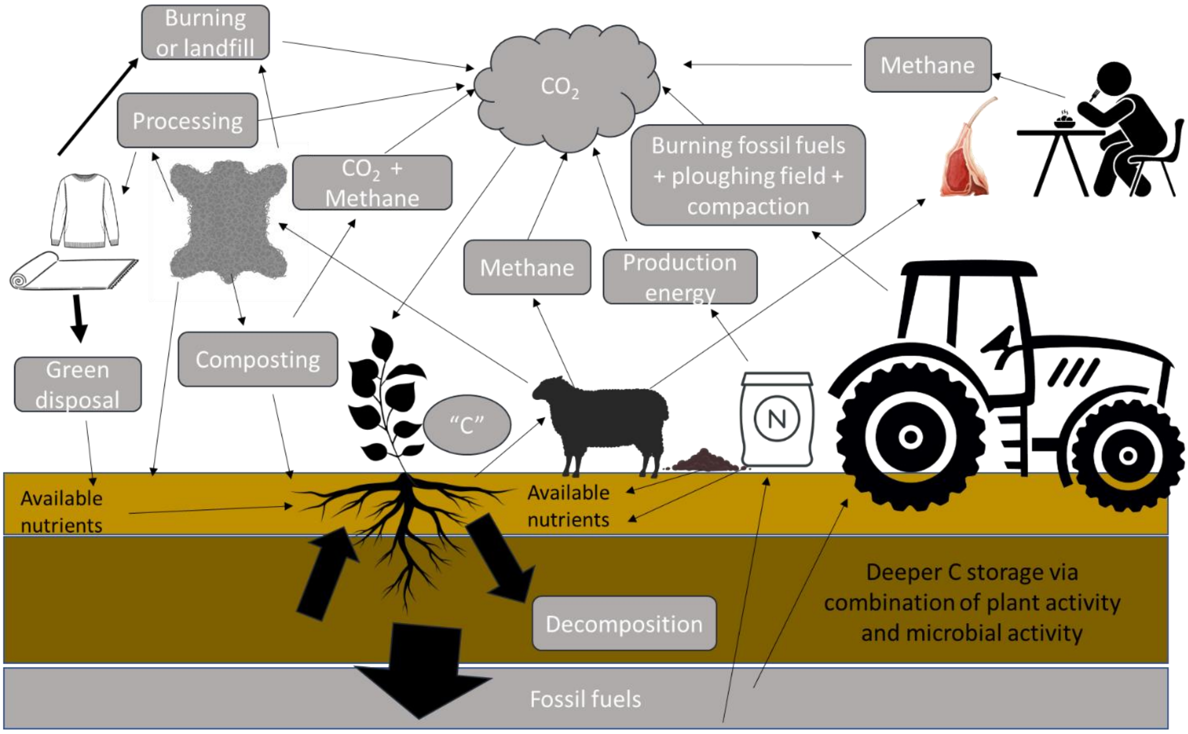
Questions posed

1. Does type of breed, climate, sheep diet, health, stage of pregnancy and time of shearing impact the carbon sequestration capacity of wool? Are there other variables/factors that influences carbon sequestration in sheep wool that Welsh farmers should be aware of?
2. Is it possible to use aspects of sheep husbandry to increase the uptake of carbon into the fleece? Taking into consideration factors such as vegetation grazed, source of water, fertilisers used, dips applied on fleece and type of farm management system used.
3. Is there a variation in wool growing rate, and hence carbon sequestration capacity through different stages of pregnancy?
4. Is there a recognised and accepted methodology to calculate a measurement of carbon removed/locked in wool over a defined period?
5. Are there carbon foot printing tools available for Welsh farmers, for free or for a fee, that considers the amount of carbon sequestered through growing wool on sheep farms?

What a search of the literature found:

One integral issue with the discussion of wool as a carbon sequestration tool is the definition of what carbon sequestration is. The heavily referenced article by Lal (2008) discusses source of sequestration and noticeably doesn't consider transient C available in for example animal meat, milk and wool at all.

A further article discussing the definition of sequestration talks about the movement of C within systems and between systems and how much of this cannot be considered sequestration unless it is significantly long term. Essentially most temporary carbon uptake and movement eventually makes its way back into the carbon cycle having minimal impact on overall sequestration. It is systems as a whole which are involved in sequestration via "pools" where carbon is stored, but, even within these pools, C is constantly fluxing in and out often over hundreds or thousands of years and it is the maintenance of balance of these pools that allows them to be considered carbon sinks or regions of sequestration. In agricultural systems such pools are essentially reliant on soil carbon stocks, though long terms woodlands may also factor in if present within a system. The same article also notes that soil C sequestration and total C sequestration should often be considered over 10- and 20-year periods at minimum and that other papers have noted wool clothing to commonly be utilised for at most 6 years on average (Laitala et al., 2015), it is difficult to suggest that wool clothing can be considered a sequestration methodology. Essentially, in most instances wool fits into the category of 'Temporarily utilized biologic C' which either via disposal of clothes, including through composting (or directly as a growth medium), burning or rotting, quickly returns C to the carbon cycle and has minimal impacts on larger global C fluctuations (Krna and Rapson, 2013).



In this simplified diagram for sheep farming systems it is clear that in traditional (non-sustainably managed) systems there are far more outputs contributing back to atmospheric CO_2 equivalent emissions than there are outputs storing carbon. The weight/thickness of the arrows in this diagram loosely represent the time taken for carbon transfer, so as can be seen there are huge amounts of rapid processes are feeding carbon out of the system but those storing carbon take much more time. Wool either through composting or direct use in soil could rapidly add carbon back to a system. Converting wool for fabric use could temporarily store carbon for slightly longer periods but then after a relatively short amount of time it will either be environmentally returned to the cycle or detrimentally returned to the cycle, making it short lived as a carbon storage system. To add to this an LCA assessment of wool textiles funded by Woolmark (Wiedemann et al., 2020) demonstrated that there are further inherent global warming potential emissions associated with retailing and wearing wool clothes that also contribute to increasing atmospheric CO_2 equivalent values. They did note, however, that these emissions could be reduced based on individual consumer use of the item (more use = relatively lower impact) and that in general these specific considerations were lower over the lifespan of the fabric than with alternatives such as cotton. The variety of processes impacting on wool textile use can be seen in the figure below, many of which require energy inputs which negate any storage achieved.

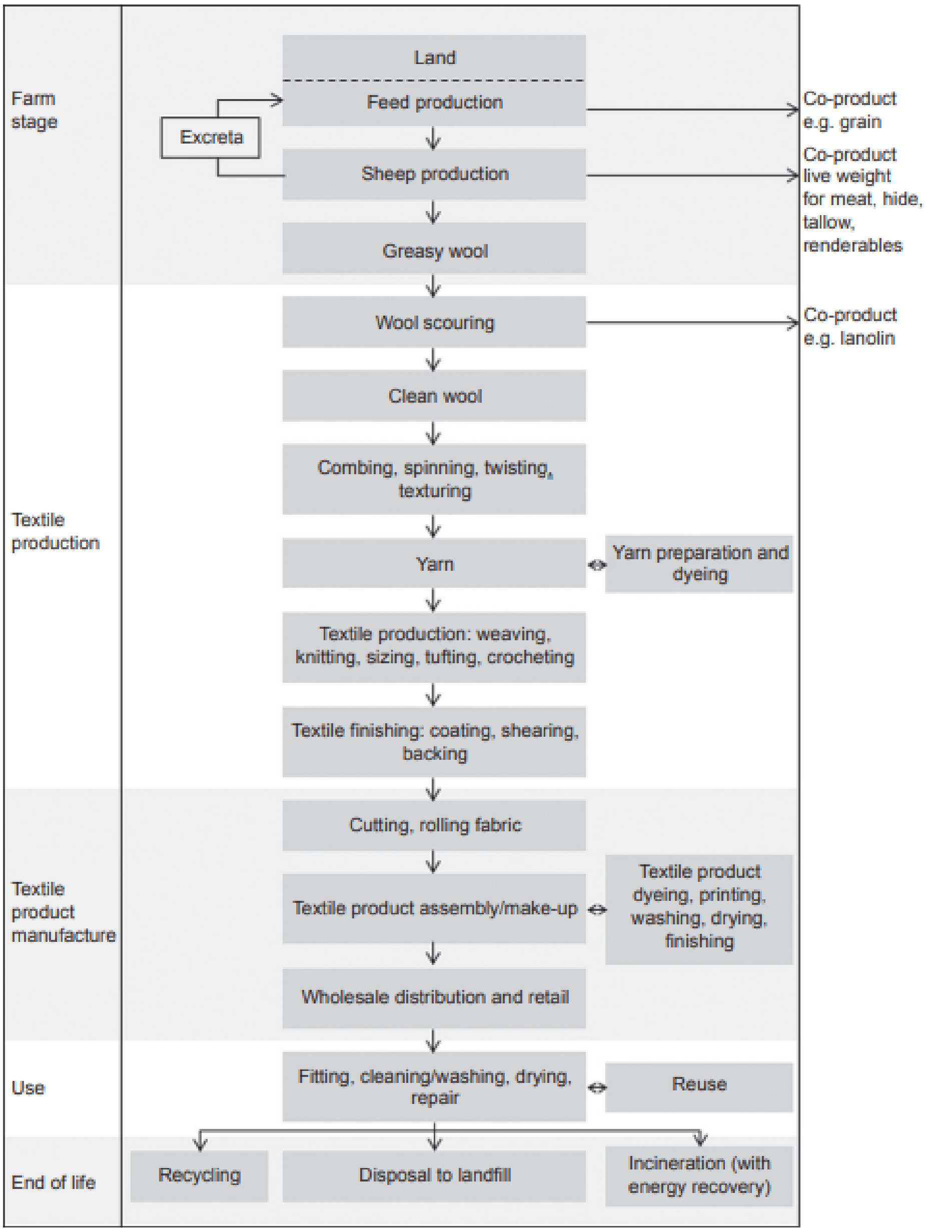


Figure 1 Processing of wool from sheep to textiles taken from (Muthu & Muthu, 2015)

Despite this there are many non-peer reviewed articles that seem to suggest wool can be a "carbon sequestration" tool. A commonly presented figure across these, that appear to lack backing in scientific literature, is that 1kg of clean wool equates to 1.8kg of CO2-e. Where this is found to be associated with non-specific articles, the reference were found to be books reviewing wool systems over 40 years ago as such the quality of the claim is dubious at best. What could be found was the composition of the material that makes up wool fibres within a fleece. The main constituent of wool fibres is keratin the same as found in hair (though in reality when considering non-cleaned weights and total fleece weights both fats, mineral matter and dirt also make up a proportion of this weight). Keratin as a compound contains 51% weight carbon based on its molecular formula (Sinha et al., 2020). And based on literature looking at extracting keratin from wool and feathers we can see that at most wool fibres contain 95% by weight pure keratin (Eslahi et al., 2013). Of note this 95% value was based on the high-quality wool producing merino breed so it is likely lower in most traditional UK breeds. Utilising these two figures above we predict that in a best-case scenario 1 kg of sheep fleece contains 0.485kg of carbon. Using calculations relating CO2 to carbon (the ratio being 44 units of CO_2 per 12 units of C) you can express this weigh as a weight of potential CO2 emissions. Whilst this isn't directly accurate, because the source of carbon would need to undergo processes to be released as CO2 which are not being factored in, it could be considered a rough approximation. Using this alongside UK average fleece weight figures (British Wool, 2010) that fleece weights range from 1 kg to 9 kg (with most hill and mountain breeds as are more applicable in Wales maxing at 3 kg's per fleece). Using 9 kg as a maximum fleece yield would give a carbon content weight of 4.365 kg which is approximately equivalent to 16kg of CO_2. Considering LCAs of meat production in the EU have a median of 32.7 kg of CO2eq output per Kg of meat produced on farm (Geß et al., 2020) and that the average slaughter weight per lamb in 2021 was 20 kg of meat https://www.statista.com/statistics/298334/carcase-weight-of-slaughtered-sheep-and-lambs-in-the-united-kingdom-uk/#statisticContainer this equates to 654 kg of CO2 eq emission over the lifespan of a lamb. Utilising other published figures gives similar results. A Bangor university study (Jones et al., 2014) suggested between 10 and 18 kg of CO_{2e} per liveweight kg lamb, using this and the common lamb finishing weight target of 45kg this equates to between 450 and 810 kg CO_2 equivalent emissions over the lifespan of a lamb. Assuming one fleece collection per lamb output per ewe this leads to CO_2 equivalent stored in a fleece offsetting somewhere between 3.5 and 1.9% of the emissions associated. This is a best case scenario and a more realistic evaluation of fleece weights and lamb liveweights or carcass weights might shift these figures somewhat (for example hill sheep might have less weighty fleeces but are also likely to have lower weight lambs that require less energy due to extensive grazing systems). This predicts that in current Welsh systems you would need between 25 and 50 fleeces to offset the emissions associated with a single lamb from birth to slaughter.

In another LCA study of the GHG emissions associated with sheep meat and wool in both NZ and the UK, different methodologies where used to look at a system from the perspective of utilising protein inputs to optimise live weight or using the protein input to optimise wool yield or a system which balanced the two. In all instances they found that the GHG emissions associated with wool production were detrimental, ranging between ~7 and 39 kg CO_{2e} per kg of greasy wool (Wiedemann et al., 2015).

What can be considered, however, with regards to wool use and production, is whether it can be a lower emission alternative to other equivalent fabric fibres whether these are organic or synthetic in their nature. By analysing and comparing LCA assessments of other fibres it could be deduced whether wool per quantity or per clothing item equivalent has a better emission spectrum or a worse one than for example polyesters. Another natural textile fibre is cotton. It was noted in a 2006 study that cotton, as opposed to wool, can achieve marginal sequestration of CO2, but only in conditions where the soil SOC values are being maintained and improved via processes such as, no or min till operations and comprehensive cover cropping strategies are used to avoid landscape CO_2 and NO_2 losses (Causarano et al., 2006). Similar statements would equally be true of wool production, in that, a no or min till pasture management and cover cropping strategies along with other environmental focused management practices would lower the general emission profiles of sheep production and this helps to make any wool C 'storage' proportionally more of a mitigator.

If we then attempt to address the specific questions:

1) Breed impacts the yield weight of wool which impacts the total weight of carbon, thus it does effectively "mitigate" more CO_{2e}. Effectively anything that increases growth, in general, tends to also increase fleece growth though specific supplements and strategies have been shown to more precisely focus wool yield. For example the additive Seleno-chitosan was noted to have roles in improving wool yield as well as daily gain and slaughter rate, and reduce the daily feed intake in multiple studies of merino sheep (Zhang et al., 2022). However, amendments have their own carbon consideration in production and transport so any utilisation of these then requires consideration to balancing any impact of improvements to the extra carbon achieved in a sheep's fleece. For example, chitosan (component of the seleno-chitosan amendment discussed previously) is largely produced from shrimp shells and crab shells and has a CO_2 consideration surrounding the fishing or farming of these animals, the processing of the shells and their transport which was noted in a project funded by the EU to range between 12 and 77 kg of CO_{2e} per kg of chitosan produced (Muñoz et al., 2018).
2) Not to increase the uptake of carbon realistically. As above the only way to increase carbon impacts is to increase yield of wool overall. One methodology for this could be in genetic control and upregulation of genes related with keratin production or selective breeding programs for improved wool growth (Wuliji et al., 2019). Transgenics and gene pathways have been assessed, though our understanding of the growth pathways still appear limited based on recent study results (Powell et al., 1994; Wang et al., 2019).
3) There are differences noted with fleece/wool quality and quantity during the pregnancy and post pregnancy periods in ewes. This has also been suggested to be linked with lamb live weight and survival in some studies as such could bear consideration when aiming to reduce the emission profile of sheep farming on the whole (as reductions in lamb survival impacts the emissions per product output and the economics of the system negatively but the total emission reduction positively) (De Barbieri et al., 2018; López-Mazz et al., 2020; Rosales Nieto et al., 2020).
4) As noted above carbon isn't removed or locked for a very significant period and very little scientific evidence is available to attempt to ascertain this other than the assumptive

calculations produced above. What is available, however, are LCA evaluations of the wool production scheme as a whole or wool production separate into cradle to farm gate and farm gate to textile production etc. These seem to demonstrate as referenced above that wool production systems are net emitters of GHG per kg of wool produced.

5) Unclear about carbon calculators as many of these are difficult to obtain data on. I would suggest whilst they will potentially factor in sheep wool as a by-product offsetting some emissions of sheep production systems they will not consider wool growth as a sequestration method.

Summary

In summary, C does move into wool from the consumption of plant material which has fixed atmospheric CO_2. This C is then temporarily stored for as long as that material is not being broken down. The time scale of this C capture is such that realistically it only temporarily leaves the carbon cycle before returning (shortly if composted, burnt, disposed, allowed to rot or used directly in soils via biodegradation - or generally within 10 years for clothing up to maximums of 20-25 years for wool carpets unless these items are recycled). As such when looking at carbon movement at a system level considering sheep farming as that system, wool cannot be considered a sequestration tool as it doesn't lead the system to have higher C fixed from the atmosphere than it releases to the atmosphere (due to enteric fermentation release of CH_4 amongst other factors). If sheep farming systems became optimised (via strategies such as land being managed without inputs of fertiliser, pesticides, inaccurate organic manure/fertiliser, no tillage, no fossil fuels and with high N fixation via legumes, year-round soil coverage, lower stocking rates, environmental focused grazing strategies) such that sheep farming could be considered net neutral with regards to C fluxes annually, then wool could technically become considered a C sequestration route within a system assessed annually or even over 10 – 20 years but only if utilised for long term textiles. Whilst it's difficult to discuss wool as an active sequestration tool what should be encouraged is its correct management to ensure it doesn't end up negatively affecting a sheep production emission profile calculation. Strategies for this have been covered in a previous technical article produced by the team which has several links to relevant paper resources

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