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Perspective

Assessing the environmental benefits of utilising residual flows

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To reduce the environmental impacts of consumption and promote a more circular economy, residual material and energy flows that were previously considered waste or surplus are increasingly utilised. Examples include the use of agricultural residues for bioenergy, the use of industrial waste heat for residential heating, or the capture and use of CO_2 for the production of chemicals. The prime motivation to start utilising such residual flows usually is to achieve environmental or economic benefits. Therefore, the question at hand is often not what the impact of a specific residues-based product is, but rather what the most environmentally beneficial use of the residual feedstock would be. This question can be answered using lifecycle assessment (LCA), but requires: i) a shift from a functional unit based on the residues-based product towards a functional unit based on utilising a residual flow, and ii) estimating what the residues-based product would replace in the 'conventional' economy, i.e. defining its *counterfactual*. Together, these two adjustments allow for a systematic comparison of the environmental benefits (or burdens) of alternative uses of a residual flow, based on LCA data.

This approach is well illustrated by two recent studies that look at the climate change mitigation potential of residual flows. Pfau et al. (2019) compared different options for utilising residual biomass from landscape management in Dutch river floodplains. It was found that energy applications have larger climate benefits per tonne of residual biomass utilised than most other applications, as the counterfactual energy generation is carbon-intensive. Thonemann and Pizzol (2019) looked at various options of utilising captured CO_2 from industrial flue gas. They found the production of polyols from waste CO_2 to be most climate-beneficial, predominantly because the counterfactual, conventional polyol synthesis causes significant greenhouse gas emissions.

Over the last decade, various other studies on residues have independently shifted towards a residue-utilisation based functional unit, and often included some form of counterfactuals to allow for intercomparison of different residue-based products. In fact, setting the functional unit at the relevant level in the supply chain has separately been flagged as a key issue in the LCA of multi-output systems (Ahlgren et al., 2015), as has the need for including counterfactuals to assess environmental impacts within a circular economy context (Millward-Hopkins and Purnell, 2019).

Here, we argue that these two adjustments to conventional LCA should always be combined and we advocate a systematic implementation of this approach in the environmental assessment of residual flows. Below, we demonstrate the relevance of this combined approach and formalise its four-step methodology using an example of the climate impact of energy carriers from agricultural crop residues (Fig. 1). In LCA terminology, the methodology can be interpreted as a consequential approach with complete and explicit substitution of the main product.

The first step in this method is to identify the residual flow-based feedstock and define its functional unit, in this example 'the utilisation of 1 dry tonne of agricultural crop residues'.

The second step is to identify the potential products that could be produced from the selected feedstock and to quantify their lifecycle environmental impacts. Products included in our example are automotive biofuels and bio-electricity. Their impacts were based on median impacts reported by Creutzig et al. (2015), while considering biogenic CO_2 emissions from this annually re-growing biomass flow as GHG-neutral. Importantly, the impacts should be calculated at the level of the new functional unit, i.e., per tonne of agricultural residue utilised. For this calculation, the biomass energy content (17 GJ/dry tonne) was based on the Phyllis2 database (phyllis.nl) and energetic

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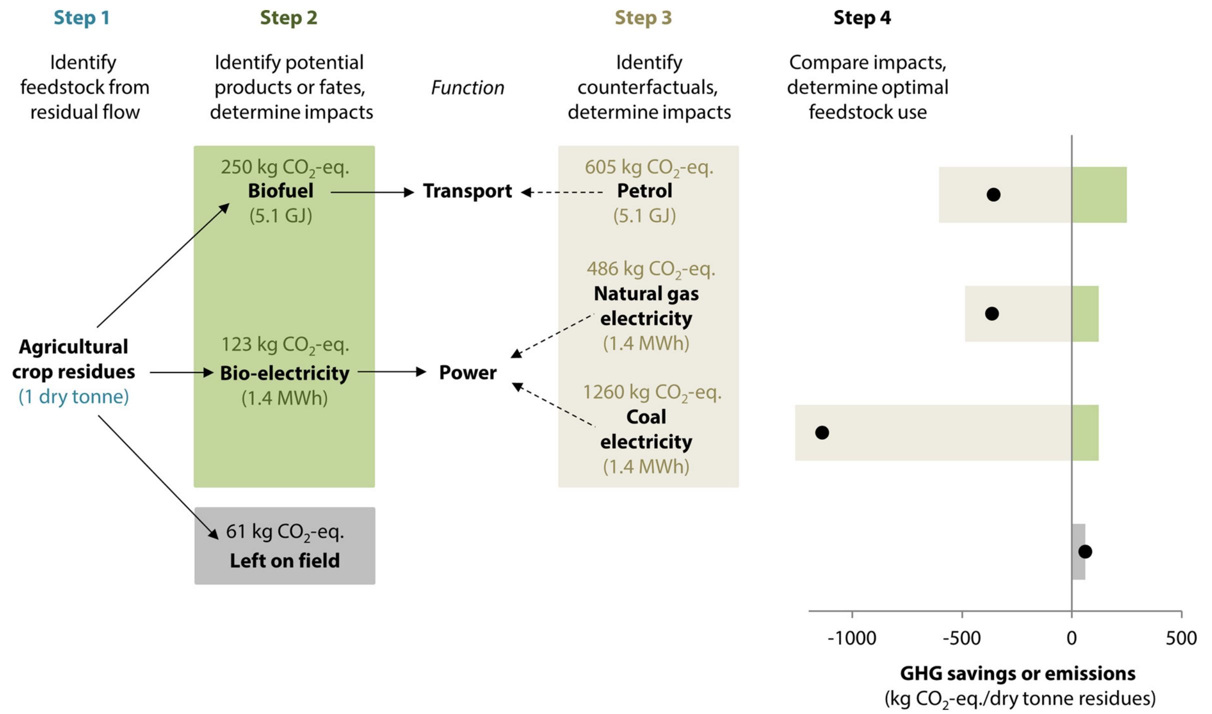

Fig. 1. Four steps proposed to systematically assess the environmental impacts of residual flow utilisation, illustrated with an example of the climate impacts of utilising agricultural crop residues. Negative emissions (light grey) represent the avoided GHG emissions of replacing a counterfactual, i.e., emission savings. Black dots indicate overall GHG savings or emissions.

conversion efficiencies were set at 30% and 40% for bio-electricity and biofuels. Optionally, the environmental impacts of what would happen to the residual flows, if not utilised, can be determined as a benchmark. In our example, we looked at leaving residues on the field. We based decomposition emissions on Pfau et al. (2019) and assumed fertiliser requirements are unaltered.

The third step is to determine what the residue-based products would replace in the conventional economy, i.e., to identify the counterfactuals, and to determine their lifecycle environmental impacts at the level of the new functional unit. In our example the assumed counterfactual for biofuel is petrol. Counterfactuals are, however, not always unequivocal. For the bio-electricity option we assumed a counterfactual of (Dutch) natural-gas based electricity, but also explored a second potential counterfactual of hard coal-based electricity. The lifecycle climate change impacts of petrol and fossil electricity were estimated using ecoinvent (ecoinvent.org).

The fourth step is to determine the environmental benefits or burdens for each option, by taking the lifecycle impacts of the new (residue-based) product minus the impacts of its counterfactual, and to identify the environmentally optimal option. In our example, utilising agricultural crop residues to produce biofuels or bio-electricity resulted in similar net greenhouse gas (GHG) savings of approximately -3.6×10^2 kg CO_2-eq./dry tonne residue (the top two black dots in Fig. 1; negative values indicate GHG savings). Note that without considering counterfactuals, the production of bio-electricity would have been strongly preferred, as the GHG emissions to produce electricity from agricultural crop residues are smaller (-1.2×10^2 kg CO_2-eq/dry tonne residue) compared to the production of biofuels (-2.5×10^2 kg CO_2-eq/dry tonne residue; green bars in Fig. 1). Clearly, erroneous conclusions would have been drawn when using a functional unit based on the final product without considering what is replaced.

What exact counterfactual is chosen for each product can strongly influence results. In our example, when bioelectricity has a different counterfactual and replaces coal-based electricity, much larger GHG savings are achieved (-1.1×10^3 kg CO_2-eq/dry tonne residue; third row in Fig. 1). What counterfactual is most realistic can be difficult to determine and changes with available technologies over time and location. Therefore, besides using a residue-utilisation based functional unit, it is essential to use case-specific and (where required) dynamic counterfactuals to accurately determine environmental impacts of residue utilisation.

A final consideration is how the absolute environmental impacts of residue utilisation should be determined. In our example, we determined impacts as compared to an absolute and hypothetical zero of not producing the residual flow in the first place. In practice it can also be informative to assess the impacts of residue utilisation against a benchmark of no residue utilisation (e.g., burning, flaring or decomposition). In our example, leaving agricultural crop residues on the field emits GHGs (61 kg CO_2-eq./dry tonne residue; fourth row in Fig. 1). GHG savings of bio-electricity and biofuels would thus increase by this amount when compared to leaving residues on the field.

The combined approach outlined in this perspective allows for an intuitive and explicit evaluation of the system consequences of utilising a residual flow, which is imperative to draw comprehensive conclusions on its environmental impacts. We believe this systematic approach can provide a useful framework to maximise the environmental benefits of residual flow utilisation.

Declaration of Competing Interest

The authors declare no competing financial interests.

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