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Potential unintended consequences of agricultural land use change driven by dietary transitions

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With a growing body of research associating livestock agriculture with faster global warming, higher health costs and greater land requirements, a drastic shift towards plant-based diets is often suggested as an effective all-round solution. Implicitly, this argument is predicated on the assumption that the reallocation of resources currently assigned to animal production systems will automatically result in the efficient cultivation of human-edible crops without negative environmental, health or socioeconomic consequences. In reality, however, the validity of this assumption warrants careful examination, as a farm's capability to adopt a new agricultural system is multifaceted and context-specific. Through a transdisciplinary review of literature, here we discuss examples of unintended consequences that could arise from the conversion of grasslands into arable production, including potentially adverse impacts on yield stability, biodiversity, soil fertility and beyond. We contend that few of these issues are being methodically considered as part of the current food security debate and call for a closer examination of supply-side constraints.

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INTRODUCTION

The scientific literature provides abundant evidence that livestock agriculture as we know it today is unsustainable on both environmental and health grounds. The sector's contribution to climate change, for example, is disproportionally large for the scale of economic activity. Out of 52.0 (±4.5) Gt $CO_2e\ yr^{-1}$ of greenhouse gases (GHGs) anthropogenically produced globally, 5.3 (±1.6) Gt $CO_2e\ yr^{-1}$ is estimated to originate from livestock supply chains for meat and dairy[1]. High consumption of red meat and processed meat has also been associated with a wide range of health risks, such as cancer, cardiovascular disease and increased general mortality[2]. Although some of these risks appear to stem from lifestyle factors correlated with meat consumption rather than compounds found in meat per se[3], from an empirical perspective, decreasing meat intake is widely recognised as an effective way to reduce public health expenditure and improve quality of life in medium and high-income economies.

Motivated by these findings, considerable efforts have been made to develop a blueprint for more sustainable diets describing what we should eat and in what quantities[4]. While the solutions proposed to date encompass a small number of novel food groups, for instance, insects[5] and cultured meat[6], the overwhelming majority of recommendations centre on a transition from animal to plant proteins, thereby calling for a contraction of livestock agriculture[7]. The optimal scale of such a shift is still debatable, as some nutritional and health challenges associated with exclusively plant-based diets are yet to be overcome[8]. Nevertheless, new knowledge is rapidly being accumulated and a consensus is starting to emerge as to how sustainable food consumption should be defined.

Where knowledge remains scant, in contrast, is food production. The current food security debate is unmistakeably urban-centric in the sense that it barely discusses what livestock farmers should do with this information[9], excluding the very group whose livelihood will be most severely affected by its outcome. In particular, future use of present-day grasslands warrants careful investigation, as present-day arable lands, on their own, are insufficient to feed the growing global population[10]. The argument for more plant-based diets implicitly assumes that at least some pasture-based livestock enterprises can convert profitably to arable systems. Furthermore, as the GHG mitigation potential of doing so is almost always estimated from *actual* life cycle assessment data[11], such argument is also predicated on the assumption that the converted enterprises will be able to produce high-quality human-edible crops, consistently and long into the future, at the same level of production efficiency enjoyed by present-day arable farms.

As a research group based in a traditional grassland region[12] but being part of an institute with a strong arable history and expertise dating back to our foundation in 1843[13], we argue that these assumptions are not robust enough to be automatically accepted. At some point in the history of human settlement, grasslands today were *chosen* to be used as such, indicating that livestock agriculture was then, and possibly still is, the most preferred land use by local farmers. If so, forcefully converting these lands into an alternative use may invite serious unintended consequences[14]. On the other hand, technological advancement since the relevant land use decision was made, and perhaps gradually became unquestioned thereafter, may mean that a subset of these lands have unrealised potential for arable agriculture, which can unexpectedly contribute to socially desirable dietary transitions.

In this perspective, we will review the current evidence in the literature and discuss likely outcomes of grass-to-arable conversion both within and beyond food production. Examples are primarily drawn from temperate grasslands in England and the

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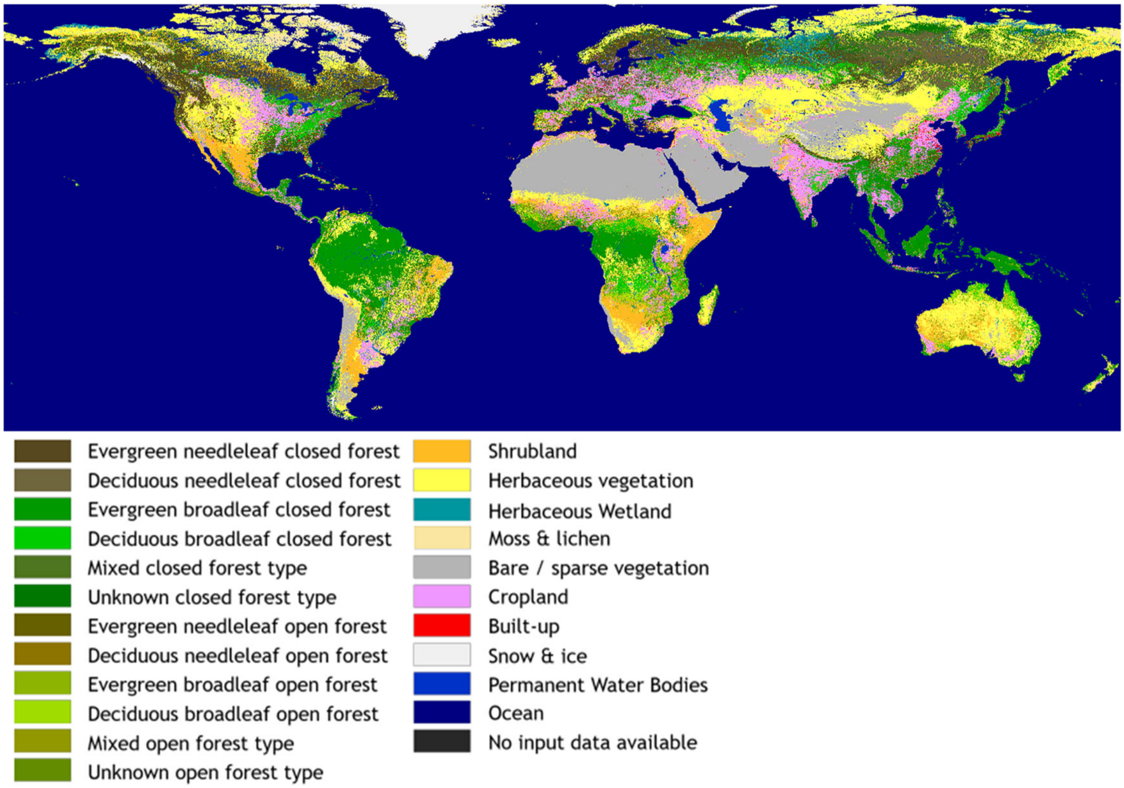

Fig. 1 Land cover map by the Copernicus Global Land Service[57], one of the three geospatial datasets used by FAO to estimate the area of grasslands. Of the 23 classes defined here, 'herbaceous vegetation' (yellow) corresponds to grassland under the UN System of Environmental-Economic Accounting Central Framework[15]. Produced under the European Union open access licence.

wider UK, although the general principle of the discussion is universally applicable as explained below.

CONTEXT: HISTORIC LAND USE CHANGE BEHIND PRESENT-DAY GRASSLANDS

Depending on the satellite imagery data used for the analysis, 18.1–30.1 million km^2 (12.2–20.2%) of the Earth's landmass, are currently defined as grasslands under the land cover classification guidelines set within the UN System of Environmental-Economic Accounting Central Framework[15] (Fig. 1). Theoretically speaking, this group of land can be further separated into primary (climatogenic) and secondary (anthropogenic) grasslands depending on the climax community at the location, i.e. whether the vegetation would be dominated by herbaceous plants or woody plants in the absence of human activities. Fossil evidence suggests that grasses became genetically capable of dominating landscapes, and thus forming primary grasslands, during the Neogene (23.0–2.6 million years ago). In contrast, archaeological evidence indicates that the history of artificial deforestation to create secondary grasslands is traced back to the Neolithic (4000–2300 BC in the case of Great Britain)[16].

Since then, however, the ecological evolution of grasslands has considerably been affected by human interventions, such as the deliberate use of fire and artificial control of plant and animal populations, regardless of their historic origins. As a result, it is no longer meaningful—or indeed technically feasible in some cases—to distinguish the two types of grasslands in the context of their optimal use except for both the extreme ends of the spectrum[17]. For example, a pronounced floristic similarity is observed between steppes in Central Asia (primary) and artificial pastures in Central Europe (secondary)[16], while North American prairies (primary) can be converted into forests in as little as 40 years under certain conditions[18]. Furthermore, globally 19.2% of the land that would climax to grassland (primary) is estimated to have been converted for arable production, despite the general perception that the environment therein is often too arid, too cold or otherwise unsuitable for intensive farming systems[19]. Consequently, the question of whether, where and how we should transform agricultural land use away from pasture-based livestock production, is equally pertinent to both primary and secondary grasslands.

In England, where the climax land cover is almost certainly forest, arable farming is thought to have become a common form of food production during the Late Bronze Age (100–500 BC), subsequently augmented by controlled (nonnomadic) livestock farming during the Iron Age (500 BC–AD 43). For the following 1500 years, both forms of agriculture were predominantly of a subsistence nature, with the geographical frontiers of farmlands rarely far-off from human settlements. Abruptly, technological development in the 16th–17th centuries unintentionally facilitated large-scale deforestation, often to create arable fields initially but then to 'demote' them to grazing pastures if the land proved unsuitable for the former purposes. This process of 'natural experiment' contributed to the formation of a more specialist landscape by the 18th–19th centuries, with light, well-drained soils primarily used for arable crops and heavy, poorly drained soils for managed pastures[20]. The bankruptcy records during the Great Depression of British Agriculture (ca. 1873–1896) attest that such land use patterns were already self-evident by then, as regions that were less affected by low cereal prices at the time overlap with those whose present landscape is more dominated by grasslands[21]. As of 2021, agricultural land use on English agricultural holdings is evenly split between arable (49%) and grass (51%) (Fig. 2).

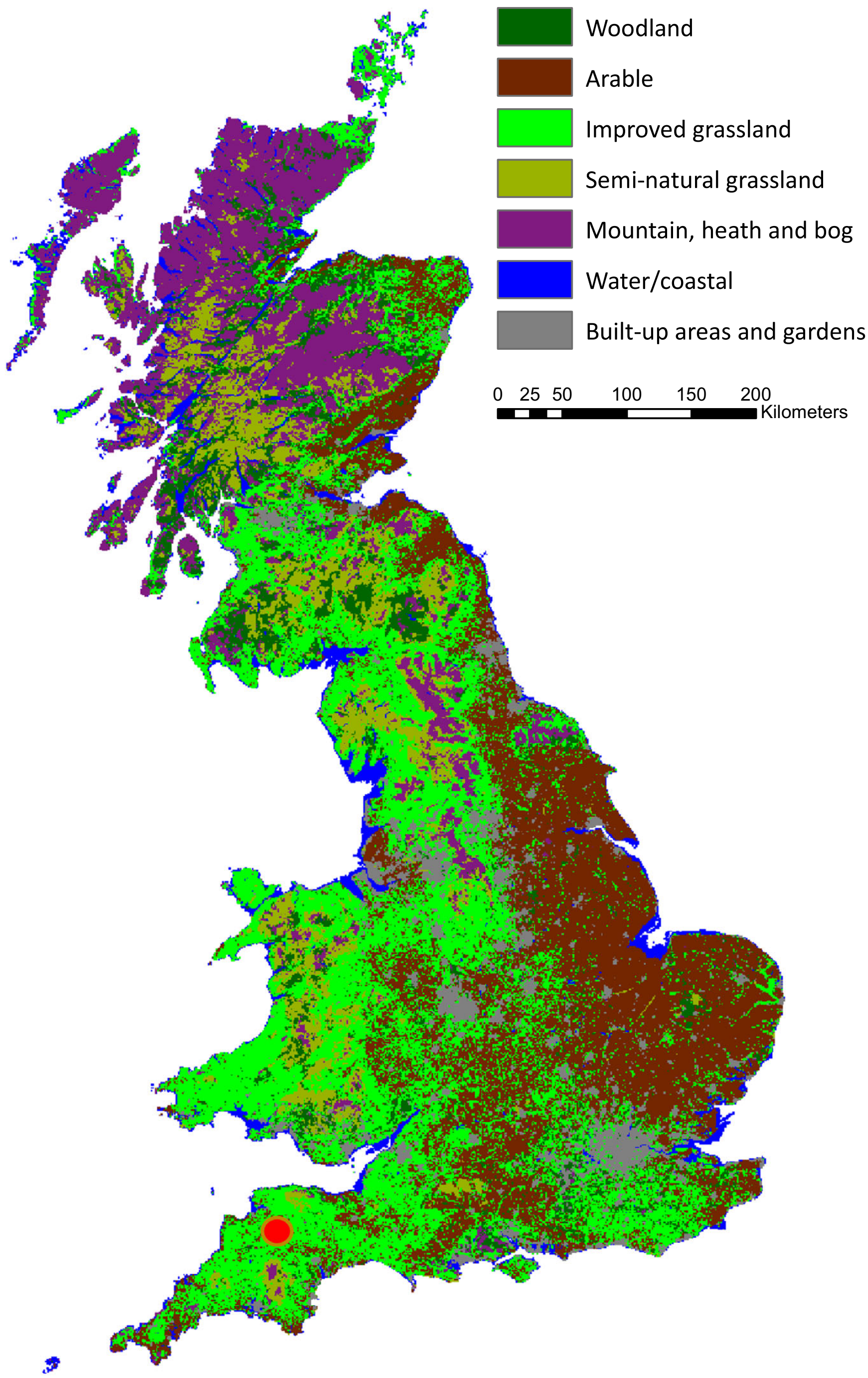

Fig. 2 Land cover map of Great Britain (2015). The location of the North Wyke Farm Platform discussed in the main text is shown with a red circle. Produced from LCM2015[58] ©UKCEH 2017. Contains Ordnance Survey data ©Crown Copyright 2007 (licence number 100017572).

POTENTIAL SOURCES OF UNINTENDED CONSEQUENCES

As is the case with any alteration to land use, grass-to-arable conversion is likely to initiate a complex set of physical, biochemical, ecological and socioeconomic changes at multiple spatiotemporal scales. Here, we outline examples of unintended consequences that could potentially arise as a result of these changes and associated hypotheses formulated from the existing literature.

Food supply

Contrary to common belief, climatic conditions of British grasslands are surprisingly suitable for arable production systems. A recent modelling study using a universal soil profile—thereby eliminating the effect of belowground water and nutrient cycles—suggests that the average 'climatic yield' of common winter wheat at the North Wyke Farm Platform (NWFP), our research base in the grassland-dominant county of Devon (Fig. 2), would be in excess of 10 t DM grain ha^{-1} and amongst the highest in the UK, owing to the combination of high temperatures, high radiation and a moderate rainfall[22]. Soil water deficit would be mild throughout the season and the winter-sown crops would mature ~300 days after sowing, following a phenological pattern that is largely comparable to the current UK wheat-growing regions. The average predicted climatic yields from northern grassland regions, where temperatures are lower, were also comparable to their arable counterparts. Importantly, these findings were robust to future climate change, even under an extreme assumption of the Intergovernmental Panel on Climate Change Representative Concentration Pathway 8.5 (RCP 8.5)[22].

Notwithstanding, actual yields of crops are inescapably affected by the specific soil profile and especially the drainage capacity, which as discussed above is likely to have been a major determinant of the past land use decisions in the first place. The soil at the NWFP, for example, comprises a slightly stony clay loam topsoil (~36% clay) and a mottled stony clay subsoil (~60% clay), both derived from Carboniferous Culm rocks underneath[23]. As such, the subsoil is impermeable to water and, anecdotally, the associated risk of seasonal waterlogging is often mentioned as one of the primary reasons for farmers' reluctance to pursue arable agriculture in grassland regions in the UK. Although historic data on adverse weather conditions seem to indicate that there will be occurrences of undesirably wet spells early in the season for winter crops[24], robust data are lacking to estimate the severity and frequency of crop damages to affect the ultimate yield. Similarly, the potential impact of late-season waterlogging on grain protein content[25] is indeterminable without further scientific evidence. It is worthwhile noting the heightened importance of product quality in the context of dietary transition, where the demand, and therefore the price, for lower-grade cereals unsuitable for human consumption would be significantly lower than today due to a reduced livestock population that currently provides the main market for low-quality grain. Combined together, the aforementioned common assumption that arable conversion will always reduce the carbon footprint per unit of human-edible food produced seems unsubstantiated; a more useful question would thus be where, and how often, it may be possible to achieve that goal.

Soil fertility and carbon stock

It is widely reported that the conversion of grassland to cropland results in a loss of soil organic carbon (SOC). Regular disturbances to soil facilitate the breakdown of physical soil structure, increasing the accessibility to soil microbes of organic carbon physically separated from microbes or bound on the surface of soil particles. Mineralisation facilitated by this process, combined with the general reduction of organic matter entering the system, collectively reduced SOC by ~36% on average over the first twenty years if the original grassland was harvested, and likely more if grazed[26]. However, most studies have only considered the SOC dynamics over the long term, and therefore more immediate impacts on soil fertility are less understood. A number of recent studies have demonstrated that, with the incorporation of the existing sward and regular input of cattle manure, a short-term increase in SOC can be obtained following the arable conversion[27]. Whether this result can be replicated in the absence of animal-originated organic amendments in a world with a reduced number of livestock, for example through the use of plant-based composts or digestate, is largely unknown.

In addition to the drastic alteration to soil structure, the change in fertilisation regime also exerts a profound influence upon the functional capacity of the soil microbiome[28] as well as its biodiversity[29]. With arable crops typically receiving greater amounts of nitrogen fertiliser, additional nitrate in the soil could act as an alternative electron acceptor for dissimilatory microbial respiration in poorly structured, carbon-deficient soils that generate greater volumes of anoxic pore space. Under this condition, an increased abundance-sensitive diversity and a decreased phylogenetic diversity of archaea are expected due to the association between soil nitrate and ammonia-oxidising archaea[30]. Consequently, it can be hypothesised that nitrous oxide emissions from a given area of soil will increase post-conversion, as discussed further below.

Nitrogen use efficiency

When animals are excluded from the calculation boundary, nitrogen use efficiency (NUE) of *grass* production systems typically ranges between 50–80%, which is largely comparable to, and at times greater than, that of human-edible arable production systems[31]. Yet, grazing livestock systems on the whole rely on two stages of nutrient transfer (soil to grass, grass to animal) rather than just one in arable systems (soil to crop), leading to a considerably lower total efficiency rate at 10–40%[32]. Theoretically, effective recycling of the nutrients excreted by the livestock, both during grazing and as managed manure, has been shown to be a key area through which noticeable NUE improvements can be achieved at a system level. Nevertheless, these nutrients are often in readily available or highly reactive forms, which are generally susceptible to losses to the wider environment[33]. Overall, therefore, we expect to see an improvement in farm-scale NUE as a result of arable conversion. That said, this hypothesis is predicated on the assumption that the yield and protein content of food produced under the new arable enterprise will be comparable to those typically observed in the current (self-selected) arable regions where existing NUE data originate. This is not guaranteed, as already discussed above.

Environmental and ecological impacts

Given that, ~43% of the carbon footprint associated with both typical beef[34] and dairy[35] production systems in the UK is attributable to either methane from enteric fermentation or nitrous oxide from manure naturally voided on the pasture, removal of livestock from a farm is generally expected to reduce the overall climate impact of the farming system. This prediction, however, may be somewhat sensitive to assumptions regarding carbon sequestration in the soil (or saturation thereof)[36]; for example, more frequent use of machinery on the arable enterprise destabilises the soil structure and is likely to trigger additional releases of both carbon dioxide and nitrous oxide through mineralisation of the soil organic matter[37]. On the other hand, soil compaction by grazing cattle leads to greater denitrification rates (and thus nitrous oxide emissions) due to increased anaerobicity, often aggravated by the locally elevated soil water content from urine deposition[38]. In order to assess the net effect of the land use change on the system-wide climate impact, these factors, their interactions and their collective feedback on soil structure must all be considered. Carbon footprinting must also account for the nutritional value of commodities produced over the full cycle of crop rotation so that the new system's GHG performance becomes objectively comparable against pre-conversion[39].

A critical driver of water quality within the context of agricultural production is fine-grained sediment flux resulting from soil erosion. Not only does this sediment flux deplete soil quality and facilitate the delivery of nutrients, contaminants and carbon to water, but it also generates negative externalities off-site, including harmful impacts on aquatic biology due to elevated turbidity/siltation[40] and higher water treatment costs[41]. Although both livestock and cereal farming can cause sediment loss above modern 'background' rates[42] and this exceedance continues despite the uptake of best management practices[43], exposure of bare soil to autumn/winter rainfall makes the risk of elevated sediment loss greater for arable fields than permanent pasture in most years[44]. However, where livestock farming does not follow recommended management, for example with over-wintering of cattle on wet ground, soil erosion rates can also be further elevated to exacerbate unintended consequences on water quality and aquatic ecosystems[45]. In this regard, a direct

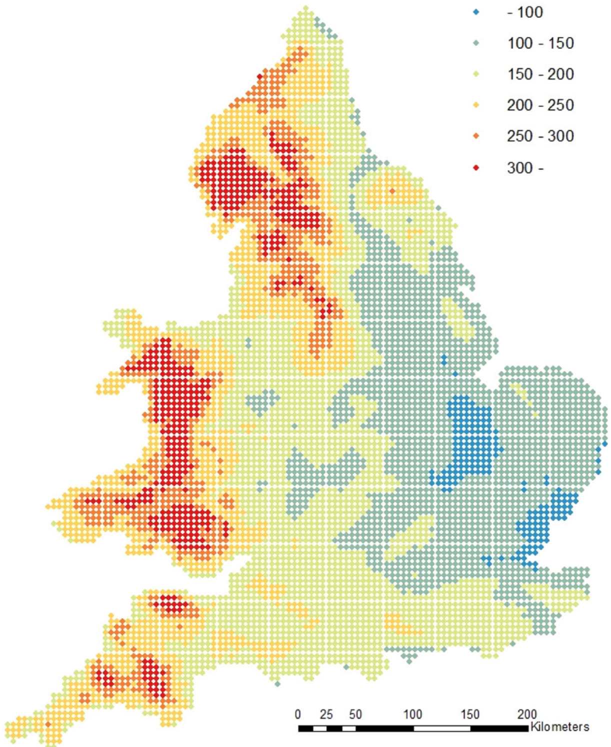

Fig. 3 Number of days per year when the soil in England and Wales exceeds the field capacity. The use of agricultural machinery is often considerably more restrictive in grassland regions (shown in Fig. 2). Produced from the UK Met Office Agricultural Land Classification dataset[54] following digitisation.

comparison between a well-managed arable system and a well-managed livestock system does not necessarily provide an accurate assessment of the impact of arable conversion, as the rate of technological uptake could differ between the two groups.

Compared to atmospheric and water emissions that are more readily observable, the impact of land use change on biodiversity is generally more difficult to quantify due to the time-lagged responses commonplace amongst plant, animal and microbial communities[46]. Nonetheless, current evidence indicates that the conversion of grassland to intensively managed arable fields is almost always accompanied by a decreased level of biodiversity in the landscape[47], although this impact is not necessarily irreversible depending on subsequent land use[48]. It should be noted, however, that superior ecological scores for grassland are often attained at the expense of fauna and flora that rely on regularly disturbed habitats such as endangered arable plant species[49]; for this reason, some taxa may exceptionally flourish under the new condition. At a coarser spatial scale, a whole-landscape transformation of grasslands into arable agriculture is neither realistic nor desirable, as some of these lands occur in unambiguously marginal conditions. Consequently, the most likely scenario following the expansion of human-edible crop production would be the creation of mixed landscapes, whose capability to maintain biodiversity is known to be considerably greater than arable-dominated land use[50]. If tactically combined with local natural habitats, these landscapes could present a novel form of the three-compartment land-sparing model[51] to simultaneously deliver food production and ecosystem services[52].

Practical constraints

While the majority of the dietary transition debates in the literature have focused on the food we *should* eat, an oft-forgotten barrier to implementing these theoretical solutions is practical constraints across the agri-food supply chain that may prevent their potential from being fully realised[53]. For example, the UK Met Office estimates[54] that the soil in many grassland regions is at field capacity for more than 200 days year^{-1} (Fig. 3). This is at least 90 days longer than major arable regions in the UK, making the use of modern machinery considerably more difficult for sowing, agrochemical application and harvesting, especially under an undulating topography. For nitrogen fertilisation, not only may this inflexibility diminish NUE[55] but also the grain quality through protein content and composition[56], which strongly affect the system-wide profitability. Beyond the farm gate, requirements for industry restructuring to support dietary transition may also pose a serious challenge. As an example, no existing grain mill within a 50-mile (80 km) radius of the NWFP has the capability to receive baking quality wheat (as opposed to feed-grade wheat) suitable for human consumption. This indicates that considerable changes to the supply chain must occur before arable conversion can become a realistic option for a large proportion of present-day grassland farmers.

CONCLUSION

The examples given above demonstrate the intricate nature of the challenges associated with grass-to-arable conversion, of which few are being methodically considered as part of the current dietary transition debates. We wholeheartedly applaud the global demand-side effort to transform our diets and the associated positive changes that are starting to emerge. Notwithstanding, we also contend that neither food security, environmental sustainability nor human health can be ensured long-term without a matching effort on the supply side.

The onus is hence on us—the agri-food and environmental science communities—to provide robust evidence to explore truly optimal agricultural land use for more nutritious food and less environmental impact. Such evidence, in turn, will likely facilitate increased dialogues between urban, rural and policy stakeholders, thereby inspiring the future of traditionally grassland regions around the world.

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AUTHOR CONTRIBUTIONS

M.S.A.B., T.T., M.R.F.L. and P.H. conceived and developed the concept. B.A.G., J.H., I.F.S. and P.H. collected preliminary data to validate the concept. M.S.A.B., T.T., L.M.C., A.L.C., T.H.M., A.L.N. and J.S. carried out the literature review. All authors wrote and revised the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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