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Farming Bounded By Our Biological Boundaries

Few people realize how their food comfort zone is shrinking. Where we are now is the starting point for an ecologically and biologically-based agricultural revolution. And it starts with the soil. We must adopt an ecosystem approach to identify sustainable food systems that can exist within our planet's boundaries, argues Stuart Meikle in the first of a four-part series.

Content

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Part 1: Setting the scene

This essay does not claim to be definitive but it is written after years of research and observation and thought, assessed with decades of relevant experience. It aims to highlight the direction of travel needed towards, and to stimulate discussion around, what sustainable food systems will begin to look like a few years down the line.

The 2020s will be a decade of substantial directional change for agriculture. The immediate post-war decade ushered in the last major food systems shift and we should expect no less a magnitude of change now.

Fortuitously, given the food situation in Europe 75 years ago, the Green Revolution was getting into full swing. The plant breeding, the fertilizers, the pesticides, and the skills needed to exploit them moved Europe from an era of scarcity to one of abundance, affordability, food waste, and even the burning of food as biofuel. Food security is of little concern to the majority, albeit that perception does not reflect the true cost of our food.

Apparently, few people realize how their food comfort zone is shrinking. We read of climate change and we read of biodiversity loss. And we hear about agriculture's pollution of air and water. We know that some regulations are removing some of the tools of the Green Revolution and that Mother Nature herself is also resisting them. And artificial fertilizers are finite, be they made with scarce, polluting, emitting fossil fuels. This is where we actually are now, and it is the starting point for an ecologically and biologically-based agricultural revolution.

It is against this backdrop that this essay is written. We need a transformational shift in our thinking about what sustainable food systems are. We have to find the answers within the context of all of the above, not just a few, vocalized issues alone.

Without question, sustainable food systems are complex and identifying them needs the multi-disciplinary thinking that is no longer common in a world of the specialist.

Sustainable food systems must work with nature, period. Nature, in past days, without us, produced abundance and we now need to tailor that capacity to fulfil our own needs, albeit this time around we must allow nature to continuously regenerate itself.

Numerous food systems will become recognized. They will be adapted for climate, location, resource availability and culture. Many will be high-tech, many not. Common to all will be the effective utilization of plant nutrients, albeit some will be unable to generate their nutrients from the soil beneath them. Those will be 'sustainable' in so far as they efficiently cycle nutrients and use renewable energy to replace those that are inevitably lost. Thus, the focus of this essay is the broadacre systems that will be needed to feed the billions, not the wealthier few.

In the writing of this essay, there is a return to the composing of agricultural policy using first the accumulated knowledge and experience of practitioners.

Policy, like food production, must be rooted in the soil.

It is written with a realization that when crises dictate action and dynamic change becomes a necessity, the extrapolation of what has immediately gone before will not provide a vision of the future. With the various systemic issues now linked to the technologies of the mid-to-late 20th century, such is where we in agriculture now find ourselves.

The next generation of agricultural systems must produce a multitude of solutions and they must be assessed accordingly. And developing them is a task made more difficult after decades of research dedicated to using our imposed tools rather than how we fulfil our needs using naturally-regenerating and ecologically-sound systems.

Defining sustainable food systems is a work in progress but we must start to make the calls now; we cannot wait for the evidence to catch up. Time is of the essence and we are addressing complex issues not well suited to the strictures of research methodology. Food systems are interdisciplinary.

Time is short and decision-making can no longer be postponed, so we have to move beyond step-by-step thinking to define a way forwards, not least because that very thinking can be rooted in the problems of the immediate past, not the solutions of the future.

Defining sustainable food systems

Ultimately, this essay is about defining sustainable food systems. There is no single answer as local climate, topography and soils dictate so much. And cultural influences play a part. Emerging, nonetheless, are principles common to all; paramount of which is that they are founded upon plant nutrition and the ability of the system to replace, or in the now common vernacular, to regenerate, the plant nutrients consumed.

We do not lose plant nutrients, but what we fail to recycle is lost to our food systems, and therein lies the crux of the matter. We eat, we wear fibres, we burn biomass, but we rarely consider the alacrity with which we use and lose plant nutrients.

If we are to safeguard our future food security, farmers will have to reduce fossil-fuel emissions, stop pollution from farming, restore and protect soils, and rebuild critical insect populations – while simultaneously dealing with the impacts of climate change and the biodiversity crisis.

In times past, successful societies achieved an equilibrium with plant nutrition. Their populaces were fewer and closer to the land that fed them. Even then, societies that failed to protect their soils collapsed.

In our own epoch we have become divorced from the land that feeds us and we have divorced plant nutrition from nature. We have seen a century of success, if gauged by population growth alone. It has come at an environmental cost and ushered in the widespread ecosystem failure that has displaced other species. We have taken the resources that feed them for our own, and when we had consumed those, we invented our own ‘solutions’ to replace them.

Sadly, we are now realizing that the environmental costs and resource consumption footprints of those solutions render them finite. We have consumed the soil carbon that sustains the biological life of our soils. It is the very life that sustains all living creatures, humans inclusive. While soil carbon loss is becoming recognized, less so is how finite are the plant nutrient sources that have enabled billions more humans to live on our bounded planet.

The history of guano tells us that we have long since found ways to outgrow the natural ability of our locality to sustain us.

For a century we have used fossil fuels to convert atmospheric nitrogen into a convenient artificial fertilizer. We have used more fossil fuels to mine eventually finite phosphates and potash, replacing biogenic nutrients with geophysical ones. Their sourcing and application both pollute and emit. They disturb and shock the rhythms of nature, the very rhythms which have fed the mass of the species that went before us.

The word finite will appear again and again as it is these plant nutrients that define the boundaries of sustainability. We have forgotten such for three-quarters of a century, and we have imperilled our food systems in doing so.

Sustainable food systems are defined by plant nutrition. As the era of fossil fuels and readily accessible artificial fertilizers moves into history, we must now address how we feed the human race’s billions.

Where do we go on a planet now becoming devoid of virgin territory? We thought the days of slash and burn were found within the pages of history books, but no, not quite. We still seek out fresh lands, resplendent, briefly, with fresh, available, soil carbon, nitrogen, phosphorus and potassium. And swiftly we degrade them.

We have nowhere to go, but still we want land to feed, clothe and power our societies. We are on a road to nowhere, and without a roadmap.

Ultimately, our destination is one where we again live within boundaries defined by the ecosystem. We must learn how those ecosystems can function to feed, to clothe, and, in part, to fuel our society.

Such ecosystems will be numerous and location specific. They must be able to regenerate what we take from them. It will be all about nutrient offtake and sympathetically managing nature to replace those nutrients. Such starts in the soil and with its biome.

As artificial plant nutrients become scarce, we must transition towards, again, relying upon nature's systems. That in itself will be difficult after decades of believing that we can dominate nature, no matter what.

Thankfully, such an approach will force us to share the ecosystems we inhabit. All biodiversity is founded in the soil and by relearning how to respect and nurture that soil we will enable nature to feed far more than ourselves.

As a society we have no choice but to change, but first we must recognize that we will only ever survive within a living, functioning ecosystem. We must appreciate that we are no greater than all the other myriad organisms necessary to ensure that the ecosystem functions to regenerate what we, the human species, desire to consume.

What has to be addressed by farmers

As a society we are facing a climate change crisis and a biodiversity crisis simultaneously. They are, nonetheless, not the entirety of the difficulties facing our farmers, a number of which, if left unaddressed, will threaten our future food security. A list of headline objectives for farmers is therefore presented below:

- alleviating climate change by targeting zero fossil-fuel carbon emissions
- working within regulatory constraints imposed upon all GHG emissions
- stopping atmospheric and aquatic environment pollution from farming
- re-establishing the biodiversity whose habitat has become farmed land

Less well publicised but, from a food producing perspective, serious issues are:

- reversing soil degradation and the widespread fall in soil-biome health
- ensuring that all our soils are protected from degradation by vegetation
- rebuilding pollinator and critical-to-food-production insect populations

A road we have to travel: Food, fibre and biofuel systems will need to be focused upon how we can encourage Nature to source and cycle plant nutrients.

- nature's resistance to conventional agriculture's solutions is increasing
- human health care must not be compromised by farm antibiotic usage
- customer demand and farmer desire for ever-enhanced animal welfare
- upstream farms will have to act as water catchments for flood control

Nonetheless, even when the above issues are alleviated, we must still address:

- our reliance upon fossil fuels for manufacturing and mining fertilizers
- mined phosphate and potash supplies are finite and inefficiently used
- energy for food will be of rising concern as fossil-fuel supplies dwindle

Plant nutrients will define the ecosystem's boundaries


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As fossil fuel access declines through absolute availability and/or regulation to alleviate pollution and emissions, we will have to return to basing our lives upon utilizing recently grown plant-based, built-upon-carbon materials.

It will be about the 'bioeconomy', a newly coined expression for how pre-industrial societies used to operate. The future will be about the production, use and circulation of plant cellulose, or specifically, the carbon therein.

Nutrition for plant growth is, nonetheless, more than about harvesting free atmospheric carbon to fuel cellulose accumulation. Plants require nitrogen, phosphorus, potassium and a complex of micronutrients. They have to be found from somewhere.

Nature sources nitrogen from the atmosphere where it is in abundance. The rest it has derived from soil and the soil biome. Humans, nonetheless, learnt how to expedite plant growth by creating and mining 'artificial' nutrients using fossil fuels to substitute for complex-to-access naturally-sourced nutrients.

With fossil fuel reserves in decline, it is to the latter that we will have to turn and it will be the supply of these biogenic plant nutrients that will define the edges of our modern-day, bioeconomy's consumption boundaries.

Hence, plant nutrients should be divided into those sourced naturally, directly or indirectly, from the atmosphere or soil profile, and those derived through humans using fossil fuels. The latter includes nitrogen from the Haber-Bosch process and mined phosphates and potash.

A well-known characteristic of artificial plant nutrition is that the utilization of nutrients is low to very low and this results in atmospheric pollution and water contamination.

Our current farming systems take resource-expensive and likely finite plant nutrients and waste them with costly consequence, albeit the full costs are rarely attributed to the food, fibre or biofuel produced. This must change.

Nature has complex but still poorly understood systems to source and circulate plant nutrients, albeit it is likely that the functionality of these systems is inhibited when easy-to-access artificial nutrients are offered.

In the future food, fibre and biofuel systems will need to be focused upon how we can encourage Nature to source and cycle plant nutrients. The caveat is then that we have to minimize fossil-fuelled human interventions used to drive nutrient cycles. We will use truly renewable energy for such activities but they will thus be constrained.

As we well know, plant growth can be stimulated with artificial nitrogen and that secures atmospheric carbon, but to what degree is that carbon naturally-sourced? Phosphates can be recycled from manure and sewage, but it often needs fossil fuels.

Hence, it is about identifying systems that use the minimum of fossil fuel or, later on, bioenergy. Conceptually it is easy, but in practice it is far from it. Nonetheless, it is a road that we have to travel.

Farming plant nutrients to provide food security

All the aforementioned issues facing farming and food production can be addressed by system change, albeit each change will impact upon the quantity of food, fibre and fuel that can be produced.

It may be argued that the yield lost through system change is too great, that yields will decline from those currently achieved, but the question should be couched in terms of what yields will be achieved, business as usual, versus system change?

If the current systems are faltering due to, for example, rising pathogen resistance, that influences the baseline against which system change should be measured. It is where we will be that counts, not what has gone before.

Absolute production is in itself an issue with both a growing global population and one that seeks to switch from fossil-fuel-based to plant-based consumption. Simply, the switch is not sustainable if total material consumption is not reduced. Plant-based derivatives are also finite.

Future farmers will require an insightful knowledge of how ecosystems work.

Henceforward, to be specific, the absolute constraint is the nutrients needed to grow plant products, be they used for food, fibre and fuel. It will be how we negotiate this constraint that will dictate our successes with future food security, but the constraint is still below the radar.

If we accept that the principal constraint on future food supplies is the availability of plant nutrients, what does a sustainable food system sufficient to provide food security look like?

The global population has quadrupled in the last century, a fact that has paralleled our use of, and now reliance on artificial fertilizers.

With questions over the geophysical availability and political access of phosphates and potassium, the fossil fuel dependency of nitrogen manufacturing and the mining of phosphates and potassium, not to mention the pollution and GHG emissions from their use, just how do we establish what a productive and sustainable food system looks like?

It is inevitable that dramatically improved utilization of artificial nutrients will have to occur, both when growing plants and with the recycling of nutrients, post plant-based product use.

Needless to say, offtake losses will still occur and we will need to find alternative ways to bring nitrogen, phosphate and potassium into plant growing systems, and with the minimum of renewable energy use. It is probable that adequate carbon will be available.

The answer will lie with understanding and utilizing how Nature creates abundance without human intervention.

Future farmers will require an insightful knowledge of how ecosystems work. It will be a seismic shift from the training many have had. Soil ecology will come to the fore.

And, with limited access to artificial fertilizers, farmers will have to manage an environment wherein plants and animals and soil microbial life function in harmony to source, share and circulate nutrients. This functioning ecosystem will be fuelled by solar energy, not fossil fuels.

Viewing farms as solar energy collectors

Open-field farms should be regarded as solar energy collectors with the energy collected and accumulated being stored within both plants and the soil biome. The energy built up within the soil is from carbohydrates exuded by plants to feed the soil biome, partly in exchange for nutrients that they cannot access from ‘locked’ sources.

In addition, the solar energy harvested enables living plants to source nutrients from the atmosphere (carbon and nitrogen) and, as stated, the soil profile via the soil biome (phosphate, potassium and the trace elements).

The nutrients then become available for other organisms to harvest, humans included, although that availability may first require the circulating of nutrients through multifarious organisms first. Under certain circumstances, excess energy can be stored as sequestered carbon, or more importantly, in accumulated carbon-rich humus.

Nutrient sourcing, cycling and accessible storage (not carbon sequestration per se) functionality defines what is the *soil fertility* available to feed later, rotational crops (which may not be able to feed themselves). And more so when the latter are grown in isolation of the plant diversity that can feed them.

Such is the case with many direct-to-human consumption food crops. And, almost by definition, monocultures struggle to feed themselves.

As fossil-fuel-based artificial nutrients become scarce, the efficiency and scale of farmland solar collection and the functionality of the soil biome will be critical. They will supplant the fossil fuel energy and artificial fertilizers used to provide food, fibres and biofuel. And such, will only ever be supplemented by artificially-lit food systems.

Recognizing what ‘offtake cropping’ is

With an increased awareness of artificial fertilizer scarcity, farm management thinking will focus upon what is being removed from the soil with each harvest.

That applies to what is removed for direct human consumption or to feed farm animals and birds. The degree of offtake being determined by how many of the residual nutrients can be returned to the soil from whence they came. The remainder will have to be supplied from the atmosphere and soil profile without using fossil fuels and the minimum of non-plant-nutrient-consuming renewable energy.

For the foreseeable future nutrient loss will also occur due to poor recycling of ‘wastes’ and inefficient utilization.

The latter will be greater where artificial fertilization occurs, as it inevitably will, albeit efficiency will be better where hydroponic and aquaponic type systems are used.

The urbanization of humans and many of the creatures that feed them, means that nutrient cycling back to the land that feeds them is near to impossible.

Nutrient sourcing, cycling and accessible storage functionality defines what is the soil fertility available to feed later, rotational crops (which may not be able to feed themselves). Almost by definition, monocultures struggle to feed themselves.

Thus, nutrient offtake for food, fibre and biofuels is inevitable and it must be regenerated by using a combination of plants, the soil biome, and solar energy working in harmony to source those nutrients from the soil profile and atmosphere.

It is a situation made worse by many of our traditional offtake crops being unable to source their own nitrogen, phosphorus and potassium, thus, making them dependent on the farmer building up soil fertility to feed them.

No doubt some could, but they would need to be grown within a system where tillage (and other shocks) are eliminated from the system to the degree that soil biome permanence allows the symbiosis between it and the plant to function.

That can only occur where the soil habitat around plant roots is stabilized to the point where bacteria can secure atmospheric nitrogen and fungi can source soil profile nutrients for the growing plant, all in exchange for root-exudated carbohydrates, the energy source for the aforementioned bacteria and fungi.

Sadly, many of our direct-for-human-use crop production systems do not enable the soil habitat permanence to exist.

Part 2: Farming to naturally regenerate plant nutrients

Building soil carbon is first about food security, second about atmospheric carbon drawdown.

Despite the climate change mitigation emphasis on carbon sequestration, building soil carbon is first about food security, second about atmospheric carbon drawdown. By working with nature's natural cycles to provide nutritious food with a low environmental footprint, Regenerative Agriculture will provide the transition from fossil-fuelled agro-chemistry to utilizing the farm's natural resources, argues Stuart Meikle in the second part of this series.


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A sustainable food system is one that will be able to generate nutrients from natural sources, and without using fossil-fuel supplied energy. Given that pre-1900 the human population was fed using accumulated soil fertility, such is feasible, for a few. Also, in times of war, the likes of Great Britain in the 1940s was also able to sustain itself briefly by exploiting the fertility accumulated in its grasslands. It was not rebuilt because artificial fertility became widely available and the economic choice.

That access to artificial fertilizers throughout the latter half of the 20th century then created a false sense of security during which real soil fertility was largely forgotten.

The rise of what is called regenerative agriculture shows that times are changing. It is all about soils and how soils can be managed to produce harvests without resorting to artificial fertilizers. As the functionality of the soil becomes paramount, so scrutiny is also placed on all that shocks the soil biome faces, be it tillage, pesticide use, or the application of artificial fertilizers (which may include unprocessed manures from housed farmed animals).

Regenerative agriculture also requires the careful consideration of system offtake, be it for food, fibre or biofuel.

Regenerative agriculture is not a single system as, unlike organic farming, it is not governed by rules. It includes practices that may also be found under the banners of organic farming, conservation agriculture, pasture-fed, agroecology, agroforestry and holistic management. Regenerative agriculture is about working with nature's natural cycles to provide nutritious food with a low environmental footprint. It is also about the regeneration of the businesses that are the heart of food production. Regenerative agriculture is a soils-first farming approach where the key is a healthy soil biome that feed plants and vice versa. The 'regenerative' reflects the focus on replacing nutrients lost to inevitable offtake (as food, fibre or fuel) from natural, 'biogenic' sources. As every farm is different and husbandry varies from farm to farm, it is not about rules but husbandry principles. Regenerative agriculture *will provide the transition from fossil-fuelled agro-chemistry to utilizing the farm's natural resources.*

Regenerative agriculture is about the interaction between the soil biome and plants. The objective is to mimic how natural grasslands can build soil fertility. This can then be exploited later for offtake cropping. When, in the past, offtake cropping has predominated, the plant-available phosphates and potassium have been consumed.

Tillage has also triggered the loss of soil carbon and with it the ability of the soil biome to function. Soils have become biologically inactive and in the worst cases physically eroded. This is a serious, global food security issue.

The operative phrase above is 'how natural grasslands can build soil fertility'. It is often forgotten that arable lands were originally grasslands or forests or, the in-between, woodland pastures. Arable land is a humankind invention that has never existed in Nature. Thus, we should not be surprised that arable lands do not function as Nature intended and are incapable of providing harvestable abundance without external help, be it in the form of artificial fertilizers, composts or imported manures.

If the artificial fertilizer availability is limited and energy limits the use of the latter two, just how are we to build arable soil fertility? It is no coincidence that broadacre organic systems include rotational crops that can mimic grassland functionality to build soil fertility.

The situation with arable land has often been made worse where decades of farming practices have reduced soil carbon and humus and biologically degraded the soil. (When people talk about how many harvests are left in our soils, always check that they are talking about biological life and not its physical state; inert soil grows little.)

The thriving soil biome contains a myriad of organisms that work as a whole. They work with a diversity of plants. It is a complexity that we are only just beginning to understand, but clearly our recent propensity for simplistic monocultures does not work. Nowhere in nature are there successful monocultures and there is a reason why. By imposing a monoculture on an ecosystem, we are still largely unaware of what we are breaking or inhibiting.

An absolute priority for farming research must be to enhance our understanding of how plants and soils interact to feed each other with carbon, nitrogen, phosphorous, potassium and the array of necessary trace elements. We will need to eventually utilize the symbiotic and diverse plant/soil-biome/animal relationships to feed ourselves.

Herbivores are an apex interactor around which many other species have evolved to live in a symbiotic relationship.

Hence, it is not by chance that regenerative agriculture is about sward diversity and polycropping. The evolution of agroforestry systems is further seeking to bring yet greater diversity into food and biofuel production systems.

As plant diversity within systems rises, either simultaneously or consecutively within rotations, how to harvest the systems with minimal, detrimental offtake is the question. Using nature-mimicking grazing by herbivores is one answer. They can sympathetically live within the plant-soil biome ecosystem while providing opportunities for nutrient offtake (our food). In the past the interactive three-way plant-soil-herbivore relationship has been able to accumulate soil fertility but, sadly, that fertility has been consumed in the 19th and early 20th centuries.

With the advent of arable farming, the challenge for famers became how to accumulate soil fertility for later offtake cropping. Thus, the advent of rotational farming systems pre-1900. Guano, be it collected from the wild or harvested from the pigeonniere or dovecote, was already in use to supplement grassland-built fertility. Night soil as a recycled, post-usage nutrient source has gradually become unacceptable or too contaminated to use.

As artificial fertilizers' fossil-fuel dependency and propensity to pollute becomes ever more evident, it will be necessary to return to systems that are able to regenerate offtake nutrients from natural sources. It will again be about rotationally harvesting plant-based nutrients to supplement animal-based nutrients without reducing vital soil functionality and fertility. It will be a case of back to the future to identify our nature-based solutions.

Where soil fertility accumulation can be done to excess, carbon sequestration can occur. Despite the climate-change mitigation emphasis on such, building soil carbon is first about food security, second about atmospheric carbon drawdown. Drawdown will occur from soil carbon building practices targeted at restoring the biological health to soils, but the climate change benefits are a consequential, but major, side effect of soil restoration.

The protection of soil carbon is a key aspect of regenerative agriculture. Likewise, with conservation agriculture.

In practice, that means maintaining vegetative cover across arable land at all times. They are called cover crops for a reason. They are also used to hold nutrients that might otherwise be lost during the between-harvestable-crop phases.

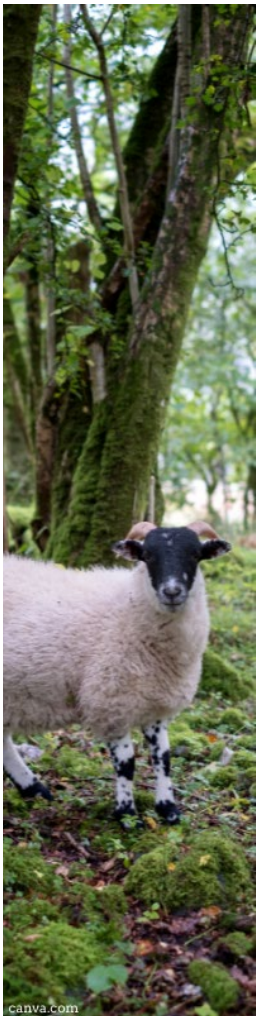
Within regenerative systems, the principle is also to ensure that there are living roots active within the soil at all times. It is they that feed the soil biome. Such non-offtake crops can also be judicially harvested by grazing herbivores, with a resultant yield of food and fibre. The

Regenerative agriculture seeks to mimic how natural grasslands can build soil fertility.

important point is that grazing practices should not defoliate the plant to the point where consequential root shed inhibits the whole, vital, soil-feeding process.

Herbivores in our food systems

Humans are omnivores with little ability to efficiently utilize plant cellulose. By contrast, herbivorous ruminants or, to be exact, the bacteria within their rumen, are able to effectively digest plants. They make the nutrients they harvest available to other species, be they in the soil biome or omnivores or carnivores. For humans they have long since been a source of nutrient-dense, nutrient-complex foods (and completely biodegradable fibres). *For the plant, the herbivores swiftly biodegrade post-reproductive-phase plant material and make the nutrients therein available for the next growing season. It is another of nature's nutrient-cycling symbiotic relationships.*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Within a fossil-fuel-free agricultural system, such a relationship creates an opportunity to harvest nutrients for human use. If the herbivore is grazing post-senescence material in situ, an offtake opportunity occurs whereby only the minimum of offtake is removed from the system, while the rest of the nutrients are recycled naturally.

In the early season, herbivores graze young growing plants. The rational is that grazing stimulates plant growth and, with some plants, encourages tillering and the formation of a greater number of seed heads. Such grazing occurs randomly with the nutrients being cycled and made available to other soil-based organisms as an energy source. They then undertake their symbiotic function. On a plant-to-plant note, grazing will offer other species the opportunity to thrive, thus improving the diversity of the whole and enabling other plants to use their own, different nutrient sourcing capabilities to the mutual benefit of all. Pre-senescence crop management offers an offtake opportunity, albeit it needs to happen within an understanding of the functionality of the whole system.

Until recently, the herbivore was a grazing creature, either herded by us humans or roaming free where they had a pivotal role within grassland ecosystems. They are an apex interactor around which many other species have evolved to live in a symbiotic relationship. If arable land is to regain some of its grassland functionality, the grazed herbivore is crucial, but so are the likes of, for example, the dung beetles that live with them. Many of our specialized landscapes have lost the herbivore and that loss will also have meant the loss of the species that evolved with them within a functioning grassland ecosystem. Food chain collapse will have also occurred.

Where herbivores are grazed within farming systems, the systems must rapidly evolve to ensure that there is minimized nutrient offtake, plant nutrient losses and fossil fuel usage.

The ultimate objective must be to produce fossil-fuel-free food and fibre. It is likely that the food nutrient to plant nutrient relationship will be important.

With the rise of artificial fertilizers, the role of herbivores as the key interactors within the natural systems that source and circulate plant nutrients has become neglected. Instead, they have gone from being fertility builders to being displaced consumers of arable-grown feeds or constrained to grazing upon monocultures that have to actually be fed by artificial fertilizers. They were once soil fertility builders but the way they are farmed now can lead to nitrate pollution and N2O emissions. It is not a great testament to late 20th century agricultural science.

However, pasture management is changing so through grazing, manuring and trampling, herbivores can provide nutrition to the species of the soil biome and, consequentially, help build soil fertility. It is that which will, again, have to underpin the provision of plant-based foods to the human diet as artificial fertilizer access declines. It is not by chance that the newer approaches are akin to how herbivores grazed pastures naturally. Tall swards are grazed heavily for very short periods before the herd moves on to fresh pastures. Sward rest periods are long.

The herbivore harvests herbage, partially utilize what they eat, and then return the residual to their immediate living environment. The various elements of the soil biome have evolved to live in a symbiotic relationship with these grazing herbivores. Ultimately everything is recycled. The human has broken this cycle through regular offtake (milk) or permanent offtake when the carcass is removed. When such happens, the constituent nutrients within the harvest are removed from the local ecosystem’s cycles. The future challenge is how to replace them.

It is possible to produce foods in animal-free farming-systems but naturally accessing plant nutrients means that such are limited. Simply, from a plant nutrient perspective, sustainable broadacre systems need grazing animals.

At the other end of the spectrum from the herbivores grazing at pasture or on rotational leys, are the urbanized herbivores that live at a distance from the land that feeds them. Not only are they dependent on feed grown with artificial fertilizers, but they are also unable to perform the grasslands functions that Nature intended for them. Inevitably, inclement weather will force farmers to house their farmed herbivores for periods, so the compromise will be to ensure that nutrients are recycled back to the land that feeds them, albeit with the caveat that the way it is done must not be detrimental to soil biome health. It will also come at an energy cost, but the opportunity should be taken to capture biogas from collected manures and to utilize that to power agriculture.

Regenerative agriculture – the full cycle

Regenerative agriculture is about mimicking ecosystems and managing them for food, fibre and fuel with offtake as both animal and plant-based products. It is about building the soil fertility from atmospheric and soil-based sources to allow later 'plant-based' offtake cropping. It is this fertility regeneration that presents the problem that farmers and researchers must resolve in the coming years. With the burgeoning population of the last 100 years, fed by artificial fertility, and demands for biomaterials and biofuels, the challenge is simply gargantuan.

Animal-free organic systems are rare for a reason. Accessing plant nutrition without them is difficult, period. It can certainly be done, and will be, but it may be unaffordable and/or inaccessible to the masses. Thus, it is very much about broadacre food, fibre and biofuel production systems and what can be achievable at scale. The key to these will be how we manage highly diverse pastures (designed to mimic natural grasslands) where the soil-biome/plant/animal interaction can thrive without the destructive impact of cultivation. Such offers the easiest options to bring plant nutrients locked within the soil profile or held in the atmosphere into our food systems.

That the same regenerative approach is suitable for restoring soils degraded by years of, for example, excessive tillage or poor grazing management is a major bonus. Although we are told that land is not being made anymore, the real question is, how much degraded land can be brought back into full functionality? In doing so, overall productive capacity may be enhanced. Further, returning vegetative cover and soil carbon can only support the functioning of the Planet's ecosystem. It may also enable habitats to be returned and biodiversity to be restored.

Maintaining the necessary plant diversity within permanent pastures to enable the soil biome to thrive must be a major part of our food systems. If they are holistically grazed and farmed without artificial fertilizers, which must be the objective, they will rebuild and/or maintain their soil carbon, thus also making them both drought resilient and capable of upstream water retention for flood control. Further, it is quite possible that access to a wide diversity of plants benefits the health of grazing animals. Such pastures are also important wildlife habitats.

It is unlikely with such a large human population that we can afford the luxury of forsaking the nutrient-sourcing capabilities of permanent pastures for rotational agriculture alone. When looked at it from the plant nutrition sourcing perspective (as the prime constraint) farming grasslands and woodland pastures will be inevitable. The lack of tillage will make it easier to maintain the functioning, healthy soil biome needed. There will be cases where other land uses can justifiably supersede the permanent pasture in food production, but we should recognize that grasslands and woodland pastures are, unlike arable, two of the Planet's 'default' ecosystems.

Likewise, when assessing land use from a sustainable plant nutrition perspective, we cannot wholesale reduce agricultural land use by intensifying crop production. It is an argument that ignores the finite nature of mined phosphorus and potassium and the fossil fuels used for manufacturing nitrogen fertilizers (including methane), mining, shipping and application, and the pollution and emissions resulting from their use.

Whenever a specific food, fibre or biofuel system is proposed, the first issue to investigate must always be the sustainability of the plant nutrients needed. The second is to assess how close the system can come to being fossil fuel free and nitrogen and phosphorus pollution free.

There are strong arguments for increasing forestry on some agricultural land, but it must also be considered in the context of plant nutrition. Pastures perceived as unproductive may be far from it when the measure of performance is food nutrients created without fossil fuel use, embedded in artificial fertilizers or otherwise.

One should also not overlook the proposed forestry's need for plant nutrients. Native, mixed, diverse woodland is another functional ecosystem that should not require artificial fertilizers. They can build fertile soils, and such have been exploited for cropping by humans. Some have done so sustainably and others very destructively.

Monoculture forestry is just that, a monoculture that has to be fed with nutrients from elsewhere. A forestry stand of trees looks attractive from a carbon draw down perspective (all growing plants draw down carbon) but that carbon is only held for the lifetime of the trees and their derived products. Ideally, soil carbon will be built by trees interacting with the soil biome beneath them, but that may not happen with forestry lacking diversity. What should, however, be factored in is the amount of fossil-fuel derived fertilizers used to power tree growth. If we do not look upon forestry as a functioning ecosystem, we may be seeing the Emperor in his new clothes.

Few people would question the importance of planting more trees. It is widely recognized that they can provide many ecosystem recovery and maintenance services, but balanced agroforestry and silvopastoral systems that can provide fossil fuel free food, fibres, biofuels and a diversity of habitats may prove to be the superior choice.

We will inevitably have to reduce the extent to which we farm animals, but the reduction must come from those that are divorced from the land that feeds them. They are too reliant on offtake crops for their nutrition. There will be cases where their ‘waste’ nutrients can be returned to adjacent land, but that will still require energy, albeit captured biomethane may suffice. And the nutrients must also be returned in a soil-biome friendly form. It is probable that farmed omnivores will eventually return to being close to the land that feeds them and to where residual nutrients can be recycled. In many cases they no longer fulfil their role in food waste recycling. That they do not do so, or where they cannot, it will bring into question their role in sustainable food systems.

When evaluating agricultural systems, plant nutrition must be prioritised as the key performance indicator (KPI). That is because it is the ultimate constraint on how much food, fibre and biofuel can be produced. It also indicates the vulnerability of a system to declining fossil fuel availability. And lost nitrogen and phosphates are pollutants.

The second KPI is soil health, typified by soil carbon and humus contents and the presence of the soil biodiversity required for functionality. A restored Soil Food Web will also help restore biodiversity. Agricultural performance will relate directly to ecosystem performance and that is complex, so beware of anyone using simplistic KPIs.

Conclusion

In conclusion, we must be sure that we are fully aware that many commonly grown offtake crops are unable to access the phosphate and potassium held within the soil profile or atmospheric nitrogen themselves (the carbon they need can be readily drawn down). Thus, they need the soil-biome/plant/animal complex to do it for them. Such is a complex that has evolved over millennia and it is the one that we must understand and work with. The fact that the soil biome contains a multitude of ultimately beneficial bacteria, fungi and microscopic creatures just makes it rather more difficult. Our neglect to acquire such knowledge has made our situation that bit worse.

However, what is increasingly clear is that we will need to manage our broadacre food-producing systems with herbivores grazing both highly diverse permanent pastures and arable cropland with rotational herbal leys and temporary cover crops. It is also unlikely that we can restore degraded grasslands, including those now classified as arable, without them. Understanding how these systems function must be the priority for anyone who wishes to partake in discussions around what are sustainable food systems because without such knowledge, simple solutions can look attractive, while the consequences of their adoption may eventually prove very destructive.

Part 3: What is methane’s role in sustainable farming?

It’s tempting to blame burping cows for methane emissions. But while nature cannot distinguish between naturally occurring methane and methane derived from fossil fuels and anthropological activity, humans can – and should. Methane has a role to play in sustainable farming. We cannot let the debate around methane emissions cloud the broader benefits of farming with ruminants, argues Stuart Meikle in part three of this series.

Is the methane from grazing herbivores the biodegradable cost of broadacre soil carbon accumulation?

Methane is a highly potent greenhouse gas. That is an established fact. It is produced in Nature from a multitude of sources naturally, and especially from wetlands. The concern is the additional methane that is generated from human activities and when the methane emanates from fossil fuels. A significant focus is also on farming and especially ruminant agriculture where microbial fermentation converts forage and feed into products that can be digested and utilized by the animal. This methane can be swiftly reduced by farmed-ruminant herd reduction.


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The key phrase above is *utilized by the animal*, whereas, *de facto*, the domesticated animal is being utilized by humankind and, thus, the methane produced by the animal is considered to be derived from anthropological activity. At its most simplistic, the human gains meat, milk, leather and various other products in exchange for placing a significant quantity of methane into the atmosphere. It is frequently considered to be a poor exchange.

The methane cycle within the carbon cycle

Prior to recent anthropological interference, methane sources would be balanced with methane sinks. Nature cycles methane. The methane cycle is considered to begin in the soil where methanogenic microorganisms break down organic matter in anaerobic condition. Such also occurs within landfills as methanogens break down the organic matter wastes, again in anaerobic conditions. In fact, methane is produced by methanogens wherever natural decomposition of organic matter occurs within anaerobic conditions. Some methane is consumed in the soil by methanotrophs, albeit this does not balance the production of methane by methanogens and the majority is emitted to the atmosphere. Nature then has the mechanisms to remove the methane from the atmosphere.

The primary mechanism for removal of methane from the atmosphere is oxidation within the troposphere by the hydroxyl radical followed by a long series of chemical reactions. The result is CO2 and H2O. Thus, methane is produced by organic matter degradation and later cleaned from the atmosphere by the hydroxyl radical over several years. Hence, the carbon from methane is then present in the atmosphere as CO2, a long-term, non-degradable greenhouse gas. Left at this stage, the CO2 would accumulate, but within Nature's cycles it does not.

Methane also emanates from fossil fuel extraction. It is all CH4, and nature does not distinguish between the CH4 from fossil fuel derivation or that methane originating from organic matter degradation by methanogens. This anthropological-caused additional methane causes atmospheric methane rises and, ultimately, CO2 increases.

The methane cycle operates with the wider carbon cycle. It is not a discrete natural mechanism but a part of the ebbs and flows of Nature's carbon cycle. The methane cycle may be considered to begin in the soil when it results from organic matter degradation, but it is produced by methanogens using organic material to generate energy to fuel their own activity. That carbon-containing organic matter may be of animal origin but, ultimately, it is itself still of plant origin. And as plants derive their carbon from atmospheric CO2, the carbon is fully cycled.

The addition of stored carbon (as in methane from fossil fuels) has exceeded the capabilities of the carbon cycle to maintain atmospheric CO2 levels and thus CO2 levels have risen. A widespread objective is now to remove this excess carbon from the atmosphere and sequester it in soils and long-life organic, usually, plant-based materials.

Where do ruminating animals fit in?

Ruminants are powered by the products created by methanogenic microbes consuming plant material. The by-product is CH4. If harnessed it is a supply of natural gas. If lost, it is a short-life, biodegradable greenhouse gas.

Were the plant material degraded naturally in aerobic conditions, it would still be converted to CO2 and its carbon returned to the atmosphere, albeit the carbon would be in a form readily available for reabsorption by growing plants. The speed of cycling means that this CO2 is not counted as a GHG, and unlike fossil-fuel derived carbon, it does not contribute to global warming. However, the residual plant material not decomposed aerobically, will first become CH4 before breaking down into CO2. This CH4 carbon may be retained within the soil, or it may be released into atmosphere, where it is eventually degraded into CO2 and H2O and becomes available for plant growth. It is important to remember that the carbon within CO2 is the primary nutrient utilized by growing plants.

Methane is recognized as a bioenergy source and manures are seen as a feedstock for bioenergy creation.

The ratio of plant material degradation will differ with conditions. In wetlands, a high proportion of it happens in anaerobic conditions and, thus, major quantities of methane are released into the atmosphere. Carbon is also retained and over millennia becomes peat. Nonetheless, on balance peat degradation in the presence of oxygen (when drained and/or harvested) is a greater GHG problem than the methane emitted by the wetlands. In such a situation, CH4 emissions are considered acceptable, even though that methane creates no utilizable products, bar the utility attributable to the restoration of wetlands biodiversity and the high cultural value of boglands.

To summarize, peatlands lose a lot of soil carbon through oxidization. The drainage of wetland is a wilful human act and the carbon lost is counted as a GHG emission. Soil carbon loss from all cultivated land and some poorly managed pastures is a major issue across all soils but can be very evident on peat soils such as the Fens in East Anglia. Rewetting peatlands will halt the anthropological soil carbon loss, but it will be replaced with methane emissions. Are they anthropological, or is it accepted that they are natural? And is the slow, natural accumulation of peat then an offset? At what point is using natural methane-emitting systems acceptable to build soil carbon?

Similarly, is the methane from grazing herbivores the biodegradable cost of broadacre soil carbon accumulation?

The point is that the carbon that enters the atmosphere from organic matter decomposition, be it aerobically or anaerobically. All originated from growing plants that utilized atmospheric CO2 and solar energy, albeit other life forms may be an intermediary. Outside agriculture, Nature balances the CO2 absorption by growing plants with CO2 and CH4 emissions, albeit there is a slow accumulation (possibly with a soil percentage and/or soil volume saturation point) of carbon retained in the soil. Henceforth, the crux, from an agricultural viewpoint, should be to avoid using fossil-fuel-emanating carbon when growing plants and practices which inhibit soil carbon building.

The methane time-lag problem

Over the last 15 years there has been a great deal of focus placed upon the methane emanating from ruminant-based agriculture. That CH4 has a global warming potential 28x that of CO2 is a well-known fact. Sadly, fewer are aware of the complex of issues around nitrogen, be it nitrates pollution in water, ammonia in the air or nitrous oxide emissions (c. 300x more potent than CO2 and 10x more so than CH4). N2O is also exceedingly long lived. In contrast, CH4 is short-lived, and biodegradable, and its carbon was initially drawn from the atmosphere by plants.

The methane cycle operating within the wider carbon cycle is natural, period. The concern is when further CH4 is attributable to human act. Thus, constant farmed ruminant numbers do not add extra CH4 and over a period of a few years the CH4 is broken down to CO2 and H2O, with the CO2 replacing the CO2 originally absorbed by the growing plant. That is how Nature evolved the system. Extra ruminants will increase CH4 for the duration of the time it takes the carbon cycle to return the CH4 to plant usable CO2. The 'extra' is not now deemed acceptable and a fall in ruminants to target swift CH4 reduction is seen as an expedient short-term carbon removal option.

There is, nonetheless, a great nuance shortfall in the above. The ruminant herd should also be considered in the light of fossil fuel usage and the emissions and pollution from nitrogen use. *It could be argued that the complex of issues around nitrogen are more long-term and damaging than those surrounding biodegradable CH4 creation.*

Artificially feeding farmed ruminants

Should the aim be to mimic natural systems as far as possible when utilizing ruminants within agriculture? As will be explained later, the ruminant provides many essential food system services and should be viewed as a strategic asset, not as a polluter of our planet. In this context, scrutiny needs to be placed upon where the plant material fed to the ruminant is linked to fossil-fuel use and artificial nitrogen use (which itself relies on fossil fuel) and, to a slightly lesser degree, the use of other artificial plant nutrient forms. These all pollute and emit. The excess focus on agricultural CH4 has diverted the debate away from these important farming-system issues.

The evaluation of ruminants within agriculture should be based upon the full complex of products and services that they can deliver (to follow). It should also be based upon differentiating the natural from the unnatural in how they are farmed. As with methane emanating from wetlands, with ruminants, the nuance is to distinguish the anthropological acts within the system from the natural ones. Ruminant CH4 reduction should be focused upon eliminating the anthropological CH4 sources while retaining the broader benefits of farming with the ruminant.

In so doing we will build sustainable food systems and not, unwittingly, undermine them via misunderstanding.

Hence, the emphasis should be on where artificial fertilizers are used to stimulate grass and forage production. The extra organic matter may be grown using fossil-fuel based stimulants, albeit it is increasingly evident that farming systems that work with nature can still be highly productive of herbage. And they will need to be given the size of the human population. Thus, the focus of ruminant farming must be on utilizing the crops that can feed themselves from the atmosphere and the soil profile. On arable land that will be extended to building soil fertility to feed later crops that the soil biome cannot feed without fertility-building assistance. It should also be self-evident that *the ruminant should not consume feeds directly emanating from this latter group of crops*.

There is a school of thought that simplifies addressing climate change to removing ruminant agriculture. That is invariably based on over-simplified assessments, and it certainly does not include all the products and services involved. Possibly, the most important will be soil-restoration-driven ecosystem-restoration. These are activities where the ruminant has strategic value. The quid pro quo is then to seek short-term climate-change mitigation by reducing ruminant numbers where they are reliant on fossil fuels and especially where the consumed plant material is linked to artificial stimulation and/or feeding human-edible crops that also rely on such stimulation.

Biogenic methane or fossil fuels

For some, it will be a difficult concept, but sustainable food systems will mean substituting fossil fuel usage with biodegradable methane, albeit the use of the latter will have to be very carefully considered. Without methane or, specifically, the energy created by methanogenic microorganisms when breaking down plant material, it will not be possible to achieve broadacre soil restoration and soil fertility building. Without such, we will not be able to sustainably grow food, fibres or biofuels. *With fossil fuels and biogenic methane, it is a case of 'either/or'*.

Further, the methane emanating from the microorganisms breaking down plant material can be harnessed itself as an energy source if captured. Liquified it can provide a mobile energy source to power agricultural operations.

Methane is recognized as a bioenergy source and manures are seen as a feedstock for bioenergy creation. Direct from the ruminant methane is not, which is reasonable given the complexities involved. The grazing ruminant should also be living in a near-to-natural environment (and thus far less reliant on fossil fuels). The question that should arise with methane as a biofuel is whether the feedstock itself is reliant on fossil-fuel linked artificial plant nutrition. If it is, its sustainability credentials are poor. Across the board it will come down to the constraints on plant nutrition and the capacity of restored, carbon- and humus-rich, functional soils to provide that nutrition.

Part 4: Targeting Fossil Fuel-Free Plant Nutrition

Feeding the soil and avoiding fossil fuels is the Holy Grail of sustainable farming. Techno-solutions aside, this will entail working with nature by mimicking nature – and harnessing the capabilities of ruminants. In the final installment of this series, Stuart Meikle outlines solutions for fossil fuel-free farming. The full series will be available as a PDF.

To recap Part Three, rumen-living microbes accelerate the degradation of organic matter to produce energy that is utilized by the ruminant. Outside the rumen that biomass would break down over a period of months or years to CO2 and, some to a lesser extent, to CH4. That plant degradation would happen. In nature, rumen degradation also symbiotically accelerates the cycling of nutrients back to growing plants.

By harnessing the capabilities of the ruminant to speed the degradation, the farmer utilizes a non fossil fuel-based energy source to produce food, several other biodegradable materials, and to build soil fertility to feed succeeding crops.

In the latter case, it is what will enable the farmer to find the Holy Grail, which is fossil fuel-free, non-polluting plant nutrition.

Fossil fuel-free plant nutrition

As far as artificial plant nutrition is concerned, what will have a constraining impact first: will it be the availability of fossil fuels for their manufacturing and/or mining, or regulation to control the pollution and emissions they cause? Either way, the production of food, fibre and biofuel relies on fossil fuels, and a rethink is now required.

Without access to artificial fertilizers to the same degree as in the past, how is agriculture to provide food, fibres and biofuels for several billion people? And that is without considering climate change or the biodiversity crisis.

Techno-solutions apart, it will be about evolving agricultural systems that work with nature by mimicking nature.

Nature can provide abundance, but whether nature can do so to meet the demands of humans is the question. However effective the agricultural systems of the future are, the nutrient offtake required by humans is vast. It is likely that reversing out of fossil fuel-derived fertilizer dependency will place more, not less, pressure on land.

This emerging industry is rapidly growing. Already, the same four mega-corporations that dominate the seed and pesticide industries (Bayer-Monsanto, DowDuPont, Syngenta-ChemChina and BASF) are moving to gain control of digital agriculture and outpace the growth of competitors.

Within the land sharing vs land sparing debate, are we even starting from the right baseline? Is intensification of less land truly realistic if plant nutrient availability and fertilizer emissions and pollution are fully accounted for? Yes, technology can help, but if nutrient losses are now about 70% to 80%, there is a long way to go to zero.

Is the more realistic scenario one where, 20 years on, agriculture is still using similar areas, albeit maybe with some withdrawal from some upland areas? It will be about utilizing land to access plant nutrients naturally and that will mean working in tune with nature. It will be about rotational agriculture to build soil fertility, and thus arable land will include fertility-building, often grazed, crops. Where the emphasis is more upon nature, it will be about highly diverse meadows and woodland pastures. And to speculate, these pasture-based systems will be a necessity as they can provide fossil fuel-free plant nutrition and, thus, foods, plus deliver for biodiversity.

Fundamental to all agricultural systems will be soil carbon and humus building to rebuild the biological systems that can naturally create abundance. It will be about soils-first farming. As there is a causal link between the use of artificial nitrogen fertilizers and soil carbon loss, is there a lack of reality about thinking that intensification of cropped land is a solution? We should be asking if such an approach will only increase our dependency on the use of artificial fertilizers and all they entail, including the full cost of pollution and their various GHG emissions.

Evaluating agricultural systems

In recent years there has been a massive emphasis placed upon carbon emissions from agriculture. Inevitably the reaction has been to base agricultural system performance evaluation upon carbon emissions. This has likely meant that greater emphasis has been placed upon carbon, although all plant life draws its carbon from the atmosphere.

Meanwhile less has been placed upon nitrogen whereas it could be argued that the complex of nitrogen-linked issues of nitrates, ammonia and nitrous oxide is an extensive, longer lasting problem. Addressing it is also a more significant challenge for an agricultural sector highly dependent on artificial nitrogen to maintain production.

While not downplaying the potential for swift climate change mitigation from well-aimed methane reductions, it is possible that the emphasis on carbon has had a detrimental effect on the overall environment.

Even when using carbon as a performance indicator, it is important to choose the right one. Is valuing food by its calorie content appropriate, or should a wider measure of nutrient density be used, albeit it may be more complex? And evaluation should not be based upon the quantity of data collected when comparing farming systems; it is about the in-depth analysis and understanding of indicative systems. It is the understanding that counts. And could there even be an inverse relationship between the data volume and the acquired knowledge?

There is a myriad of farming issues to address at present, the entirety of which may not be addressed effectively if the carbon footprint is the initial indicator of performance. It is possible, even probable, that the best carbon-farming systems will be those where carbon performance is the cumulative result of the many system changes needed for a system to mimic and work with nature. A few other key performance indicators (KPIs) are listed below:

- fertilizer (especially nitrogen and phosphate) use per land unit or per unit of food nutrient
- plant nutrient losses (which is more complicated) per land unit or per unit of food nutrient
- fossil-fuel usage at all points within the system per unit of land or per unit of food nutrient
- antimicrobial usage per unit of food produced or, still preferably, food nutrients produced
- offtake crops (typically grains) fed to farmed animals per head or food nutrients produced
- soil carbon percentage and soil volume to indicate system health (not sequestered carbon)

Yes, these measures are far more complicated than carbon emissions and that is why they should be used on an indicative systems basis. There is a vast amount of data being collected on carbon emissions from agriculture, but that data is collated using rules designed to accommodate that collation. Thus, they can be very broad-brush and over-simplified. It is unlikely that they will be suitable for evaluating complex working-with-nature systems.

With the last KPI, it should be noted that soil carbon building is not about offsetting fossil fuel-derived emissions, it is about creating the plant-growing environment that will allow the reduction (and maybe removal) of fossil fuel-derived artificial fertilizers every year from here on in, ad infinitum.

Restoring the soil habitat is the equivalent of giving a person a fishing rod instead of a fish. Soil carbon is about the long-term offset of GHG emanating from fossil fuel-based fertilizers. It is also about the cost of mitigating the impacts of their residuals. It is also about N2O and ammonia reductions. *These are the main reasons for soil carbon building rather than carbon drawdown alone.*

Grazing-ruminant methane is a cost that will be incurred to rebuild broadacre soil carbon and to maintain that soil carbon given that offtake cropping itself frequently degrades soil carbon. Their manure is also a vital tool in transferring plant nutrients between farmed crops, be that in terms or time and/or space. These are essential functions for food systems. They are also vital for farmland biodiversity recovery. Such will, however, not happen if grazing ruminants have already been ruled out by carbon accounting rules based assessment. Hence, when placed and assessed in the right context, ruminant methane is seen to underwrite sustainable food production.

A fossil fuel-free farming focus

The term ‘fossil fuel-free’ should be primarily considered in two contexts in agriculture. It is about the reduction in direct fossil fuel usage for power and its use to manufacture, mine, deliver and apply artificial fertilizers. Fossil fuel-free may also be applied to specific fossil fuel-based inputs like plastics and pharmaceutical and pesticide manufacture. Where fossil fuel fertilizers are used there is also the associated costs of N and P pollution removal.

At present, producing fossil fuel-free food to feed billions of urban people is a pipedream. By the end of the century people will look back and realize that it was not and that targeting such was just another step in the evolution of human civilization. It will result from the careful use of genuinely renewable energy (i.e., not that associated with crop offtake) to replace fossil fuels and the use of food systems powered mainly by solar energy.

At the forefront of this agricultural revolution will be the focus on the plants that can be fed by the soil biome. It will be about feeding the soil to feed the plants. And offtake crops will be fed by the plants that can operate symbiotically with the soil biome and leave a fertility residual for the next crop. Increasingly, one can expect that polycropping will enable the symbiotic plant-to-plant relationships to work simultaneously, not consecutively.

Is it purely coincidental that focusing on a plant diversity that can secure its own nutrients from the atmosphere and soil profile is to focus upon the soil biome and its interaction with plants? Or that, for that to happen, the focus must be on building and maintaining the soil habitat and carbon? And that itself needs grazing herbivores, and especially when the farmer is seeking to accelerate natural degradation, as indeed must happen.

This is all about relying on the systems evolved by nature, but they cannot happen if one key part is missing. When it is, as in the past, fossil fuel-based – or before that, manual, human energy – is used to plug the gap. *Trying to design a food system by deliberately removing one of the fundamental components provided by nature is to invite failure.*

A consequence of the above is soil carbon building and when this occurs at depth and within farming systems designed to safeguard it, carbon drawdown will occur. To what degree will vary with farm, soil and system. It is not easy to quantify or measure. Further, the importance of protecting soil carbon will mean ensuring that soils are protected by vegetative cover and that will improve the local ecosystem.

The emphasis on atmospheric and soil-profile nutrient sourcing for plants naturally will also reduce the vast nutrient leakage that already occurs (Nature's systems would simply not have evolved to tolerate nutrient loss; nature does not function that way). Those lost nutrients have a fossil-fuel footprint and emit and pollute.

All of this is beneficial to the fight against climate change, but just how much of this actually falls within the bounds of carbon accounting methodology?

Fossil fuel-free product creation

In the first instance this will be based upon harvesting those plants that can feed themselves. A few pulse crops are, at least from a nitrogen perspective, capable of feeding themselves. As said, others will emerge through the development of polycropping systems where symbiotic relationships can enable the whole to be self-sustaining in terms of plant-nutrient access. By definition, their management will be far more complicated than monocrops.

Further, where soil aggregation is allowed to occur around plant roots, anaerobic 'pockets' are formed that allow nitrogen-fixing bacteria to drawdown atmospheric nitrogen. This is exchanged for root-exudated carbohydrates in a symbiotic relationship with the growing plant. The bacteria themselves obtain their energy from the sun via the photosynthetic activity of the plant. A similar relationship exists between mycorrhizal fungi and plants with the exchange being 'liquid carbon' for soil-profile-held nutrients. These are natural, fundamental relationships.

The important factor is crop permanence and much reduced (or zero) tillage. This contradicts the situation where so many current human offtake crops require tillage, are non-permanent and contradict the soil habitat stability needs of the naturally functioning nutrient-sourcing and transfer systems. Into the future, our sustainable food systems must be built upon soil habitat, and thus crop permanence. With the scale of the human population's food, fibre and biofuel needs, we cannot forsake opportunities to harvest these crops. And, incidentally, these crops are also more resilient in a changing climate, including one where drought becomes more commonplace.

Grazing herbivores, and to a lesser degree, omnivores play a key role in allowing fertility building crops to provide for succeeding fertility consuming crops. Many of our mainstream food crops fall into this latter category. Such is the importance of the grazing animal in bridging the fertility succession gap, it is possible that grazing animals are required in food systems even if we choose not to harvest their products. Such an approach would certainly reduce the total productive capacity of the system, but the point illustrates the importance of grazing herbivores.

Instead, as said earlier, animal-free growing systems are possible, but they will probably be unable to deliver the broadacre scale needed to feed several billion people. They will, nonetheless, be a key food system component.

Lucerne (alfalfa), sainfoin, trefoils and vetches will be the key agricultural crops, at least in temperate climates. It is not by chance that they are all capable of fixing their own nitrogen. Even then, the plant diversity within a pasture, be it permanent or rotational, needs to be far greater to include plants that are adapted to sourcing other nutrients from the soil profile, some of which are not in an accessible form to many crops. These typically deep-rooting herbs also enhance the pasture's drought tolerance.

Plant diversity is also likely to make available plants with medicinal properties, while others have anthelmintic capabilities. The latter are likely to become invaluable as resistance to wormers rise and the knowledge of their residuals on soil life becomes better known.

As stated before, there will be increasing use of companion planting and polycropping. In the latter mechanical separation techniques will be important, and that will also mean mixed crops that can be harvested together. It is not by chance that vetch and oats (or barley) have historically been grown together. In some climates they can be harvested together and separated; in others their use may be limited to harvesting them green for forage.

Hence, we have a situation whereby many of the crop plants that can sustain themselves (but still most likely within a diversity) can only directly be utilized by herbivores. The human simply has not evolved the digestive tracts to consume them. These crops are to be found in permanent pastures or fertility building herbal leys or in cover crops used to protect soils and/or build fertility within arable cropping rotations. On a broadacre farming scale, these crops have to be grown and given the size of the human population, somehow indirectly utilized.

Thus, if we are to live without our reliance on fossil fuels, harvesting herbivores for meat, milk, fibres and their many by-products (the value of which is typically not considered in too narrow evaluations of sustainable food systems). When it comes to *the 'eat less meat but better'* mantra, the better must start with questions over the farming system's reliance on fossil fuels and especially artificial fertilizers that are mined or manufactured using fossil fuels. This is a far better indicator of performance than using overly simplistic carbon emissions counting.

Fossil fuel-free power for agriculture

The herbivore up until 100 years ago powered agriculture. In many locations it still does. Horses, asses, donkeys, oxen and water buffalo all still provide tractive power for cultivation and transport. And, unlike the internal combustion engine they only require biomass to feed them. They are also finally biodegradable. As the soils-first approach to farming becomes the norm, there may increasingly be niches for their use again. Less-cultivation tillage will mean less power is needed and some re-evaluation of techniques will follow. It is, however, inevitable that mobile power will be needed, and the engine-power source-options include electricity and biomethane gas.

Biomethane can be used as a direct engine fuel or via conversion to electricity. Sadly, its capture from animals directly is likely to be limited so it will be about using slurry and farmyard manure as a feedstock for anaerobic digestion plants. Crucially, as the feedstock includes valuable plant nutrients, the residuals from the process must be recycled back to the land. There are, however, numerous system questions to ask, such as:

- are (aerobic) composting barns a better option altogether when winter housing is a necessity? Is the product useable by the horticultural sector? Are there animal welfare benefits? Are there also housing cost benefits?
- can forage plants as a direct feedstock for anaerobic digesters be justified if they are seen as nutrient offtake crops? It is not just about carbon emissions; it is about cycling all plant nutrients. Can the feedstock nutrient offtake be balanced by nutrient return? Can the whole be seen as a closed-loop agricultural power source?
- should energy created with agricultural feedstocks only be viewed as energy to power agriculture and food?
- as it is essential to use food waste and below food-grade produce, should this go to anaerobic digestion? Or should it go to feed monogastric pigs and poultry first?

> The systems can be circular, but to what degree do they culminate in plant nutrients being returned to the land? How much energy is needed to close the circle?

An important overall question for all biofuels is whether they can be produced without consuming artificial plant nutrients. It is an issue for food, and it will be for fibres, but it is a major issue for biofuels. Hence, is it possible for the plants utilized for both biofuels and biomass (including that used for biomaterials like bioplastics) to regenerate the plant nutrients used naturally? Or are they also fossil fuel-dependent and, thus, an illusion?

Fossil fuel-free service provision

As we move into an era where fossil fuel usage is scrutinized and there is a greater reliance on renewable energy, land management by herbivores will be a valuable tool. In some cases, it may be a direct choice between the use of fossil fuels and CH4 emissions (as the by-product of energy creation by rumen-living microbial life). The situations are varied, from amenity land management, to clearing leaf debris to prevent forest fires, to creating organic matter to reverse desertification of soils. It is again about looking at ruminants as a strategic resource.

High Nature Value land management

There are many examples to be found where grazing herbivores have been found to be the best tool to manage land recognized as being of high nature value. Often this is a direct alternative to mechanical or manual methods. With the former, the methane produced by the grazing animal should be considered as a substitution for fossil fuels. Further, there will also be food and fibres produced if the choice is made to harvest them. It may not be. It may be that the conservation management services are sufficient in their own right to justify the CH4 produced.

It should be noted that the HNV land area is not fixed. In some cases, land use and/or management changes may enhance the value enough for it to become considered HNV land. To achieve such status, the grazing herbivore may be the most effective tool. This will also not be limited to creating HNV land that is then *reserved for nature*.

The United Kingdom has lost 97% of its HNV wildflower meadows since the ploughing-up campaigns of World War Two. This was to harvest their stored soil fertility. They did not return as artificial fertilizers meant that they could be maintained as arable land or ‘improved’ as pastures with newly bred, productive grasses (albeit they relied on artificial fertilizers). The misnomer is now that wildflower meadows need poor soils and are not, when established, agriculturally productive. The remnants are now just found on poor soils as they were unsuitable to tillage or ‘improvement’. Plant diversity and the soil biome does not function well when artificial fertilizers are used so there is the belief that soil fertility is the enemy of ‘wildflower meadows’, whereas it may be necessary for the soil to go through a ‘detox’ phase before the soil biome and plant diversity function effectively. Anyone familiar with the meadows of Transylvania will know that plant biodiversity and soil fertility go together to create abundance. We have just lost the knowledge to recognize such and to manage wildflower meadows to do so.

High Cultural Value land management

There are landscapes that have become iconic and culturally valuable. Often, they now have tourism value. This may, nonetheless, be a transitory situation with perceptions changing over time. In the meantime, some land can be designated as of high cultural value with society choosing to see it managed accordingly. Across the HCV land spectrum, techniques will vary with some requiring energy-using mechanical methods (they may transition away from fossil fuels to renewables) while others will use grazing animals, with CH4 substituting for fossil fuels.

Carbon sequestration and its storage

One will not be able to avoid the term carbon farming in the coming years and there will be a suite of carbon related activities linked to farming. *Cultivation loses carbon while (some) pasture-farming can restore it* is a simple message. But Conservation Agriculture is now providing many husbandry techniques to protect tilled-soil carbon while some grazing and/or fertilization approaches can lose carbon from grassland. It is a complex issue, and such is reflected in the often-held view that *if it cannot be accurately measured it cannot be included* in the carbon assessment of farming (carbon farming or otherwise). That is not a useful message to send to a critical land use sector when it comes to identifying sustainable food systems, including those that can also significantly contribute to planetary ecosystem recovery via the restoration and then the management of degraded soils.

The body of evidence around building and protecting soil carbon is still evolving as, for decades, ‘Soils’ was the Cinderella of agriculture. *Soil biome feeding plants* was not considered an essential subject when we had abundant artificial fertilizers and rather less knowledge of the consequences of using them. Instead, what has evolved is a knowledge base created by a largely informal network of farmers, researchers and advisors. It is possibly stronger for its diversity. Such is the imperative of the climate crisis, it is likely that this knowledge will move into mainstream agriculture, while formal research plays catch-up. It is a situation that will make it difficult to reward farmers for carbon capture. It should, however, be noted that such is a secondary activity; the priority must be for farmers to build resilient farming businesses, and that will itself drive their desire to capture carbon.

It is likely that carbon farming that involves stable carbon storage at depth will need the symbiotic soil biome /plant/grazing animal combination to work effectively. It is probable that targeting such functionality will also mean the minimization of the shocks to system that come from using artificial fertilizers and pesticides and the residues from pharmaceutical products. Minimal cultivation and cover crops will be necessary to protect that soil carbon during offtake cropping periods. Within broadacre agriculture, at several points, ruminants will be an essential, productive tool. They may emit CH4, but this must be balanced against their carbon-farming role.

Biodegradable ruminant products

The ruminant animal, whether domesticated or not, has provided humankind with a source of fibres since pre-history. At the point where they are a raw material for processing, they can be fossil fuel-free. Processing aside, at this point they must be compared to functionally-comparable fossil fuel-based fibres. The former utilizes fully biodegradable methane for their production (albeit with an atmospheric degradation time lag), while the latter uses fossil fuels. The former is biodegradable with their carbon being returned to the atmosphere via aerobic or anaerobic degradation, depending on whether that degradation takes place in the presence of oxygen or not.

If, however, that degradation occurs within the anaerobic conditions of a landfill, that carbon will first become methane and then, only later, CO2. Such will occur with the disposal of both plant-based and animal-based fibres.

The half-life of non-organic, synthetic, fossil fuel-based fibres may be hundreds of years with all that such entails. They may also create microplastic pollution during use (for instance, when laundered). Such microplastics may also render sewage and municipal compost unusable for plant production, thus incurring the loss of those plant nutrients to agriculture. Their replacement will also have to rely on natural regeneration without fossil fuels. The cost of synthetic fibres can be multiple and often go well beyond the ‘they are not biodegradable’ issue.

Finally, and frequently overlooked, the fibres produced from ruminants may sequester carbon for many decades. Wool and leather may have a longer fixed-carbon life than say coppiced timber used for biomass or softwoods turned into pallets and packaging. These are yet more factors to consider when evaluating agricultural systems.

Farming bounded by biological boundaries

This essay, including its earlier ‘soil-carbon primer’, covers the complex issue of how to create the sustainable agricultural systems that can work within the biological boundaries of the Planet. Such can be simplified to a degree, but any simplification is fraught with dangers. And such has happened to fit agricultural complexity into a carbon-based accounting system. Farming is not all about carbon: it is about much, much more. It is also not just about climate change; it is not even just about the biodiversity crisis – it is about a very great deal more.

The objective of the essay has been to demonstrate this, but also to show that there are relatively simple solutions to complex problems, once we start to understand how Nature can function to deliver our needs.

Plant nutrition sourcing and management in its totality is the central pillar to future sustainable-farming thinking and delivering nutrients regeneratively must drive our choices. And, like it or not, grazing ruminants with their methane-emitting power source are an integral part of the soil biome/plant diversity/herbivore nexus that Nature has evolved to manage grassland (albeit now converted to arable) and woodland-pasture ecosystems.

About the author

Stuart Meikle is an agricultural management and policy specialist, an economist, a writer and an advisor. He was brought up with agriculture and studied at the University of London. He joined the faculty on graduating and spent several years teaching, researching and consulting. His last 25 years have seen him advising governments, the World Bank and the IFC, NGOs, universities and private businesses in places as far afield as SE and Central Asia, the Caucuses, the Levant, SE Europe and the UK. Over the years he has developed a particular focus on agricultural and food sector strategy at the national and regional levels and linking rural development initiatives with the consumer through the food supply chains. He first arrived in Romania to work on a Commission project in 1997 and he lived in Transylvania for more than a decade from 2002; a location to which he was appointed as the United Kingdom's first Honorary Consul. Nowadays he and his family live in the Republic of Ireland.

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