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Review

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Practical paths towards quantifying and mitigating agricultural methane emissions

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This review summarizes the rapid advances in direct practical methods to quantify and reduce agricultural methane emissions worldwide. Major tasks are location, identification, quantification and distinction between different specific sources (often multiple emitters such as manure pools, animal housing, biodigesters and landfills are co-located). Emission reduction, facilitated by developing methodologies for locating hot spots, is the least-cost choice for action, especially from manure stores, biodigesters and from controlling biomass burning. Agricultural methane can also be used to generate electricity or, in appropriate circumstances, can be destroyed by oxidation. It may be possible to cut North American, East Asian and European emissions sharply and rapidly. In Africa and South Asia, emissions from crop waste and food waste in landfills, also a source of air pollution, can be sharply and quickly reduced. Globally, cutting total annual agricultural and waste emissions by a third would demand reductions of very approximately 75 Tg yr^{-1}. Apportioned by source type, notional cuts might be 30–40 Tg yr^{-1} from livestock and manure, 5-10 Tg yr^{-1} from rice cultivation and 20 Tg yr^{-1} or more from specifically agricultural waste.

1. Introduction

Agriculture is the largest anthropogenic source of methane [1]. Failure to reduce global agricutural methane emissions will put the goals of the Paris Agreement out of reach [2]. The United Nations Food and Agriculture Organisation [3,4] has called for sharp reductions in gross agricultural emissions of methane, while the Global Methane Pledge has committed over 150 nations to 30% cuts in gross anthropogenic emissions by 2030. The first part of this review summarizes the current growth of atmospheric methane, placing it in the context of climate change. We discuss rapid advances in quantifying agricultural methane sources, and consider ways to control and mitigate methane emissions. Finally, we suggest possible pathways and targets for reducing emissions.

2. Methane's recent growth rate and isotopic shift

The amount of methane in the air is growing rapidly [5,6]. After an approach to steady state, the increases since 2006 were unexpected, and the high growth rates since 2020 have been remarkable [7]. The record of the US National Oceanic and Atmospheric Administration (NOAA) (figures 1 and 2) clearly shows the strong growth pattern since 2007, when the period of equilibration in the early 2000s ended. Accompanying the recent growth, methane's isotopic shift to more ^{13}C-depleted values (figure 2, lower panel), which began in late 2006 and 2007, is reversing a centuries-long ^{13}C-enrichment trend. This suggests methane's current growth is dominantly caused by increases in emissions from biological sources [6].

Methane emitted from fossil fuel and biomass burning is comparatively rich in ^{13}C and drives $\delta^{13}C_{CH4}$ positive, upwards in figure 2, while biologically sourced methane emission, from wetlands, agricultural ruminants and biowaste disposal in landfills, sewage, etc., drives $\delta^{13}C_{CH4}$ negative, downwards. $\delta^{13}C_{CH4}$ in methane from the South Pole is shown in figure 2.

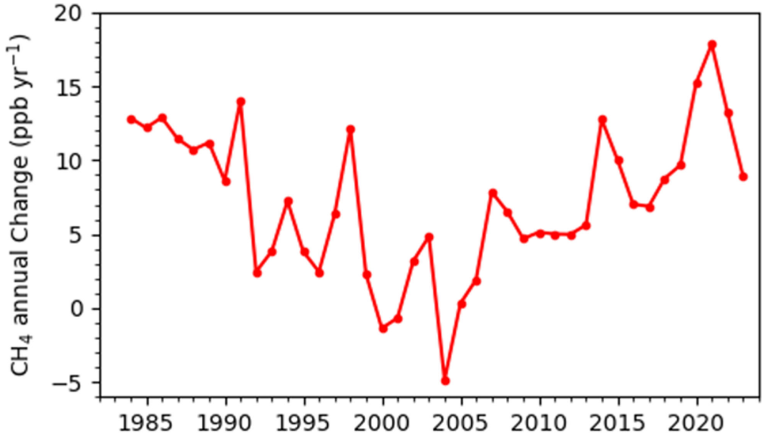

Figure 1. Annual global increase in atmospheric methane 1984–present. In four decades, only 2004 has seen a significant decline, and annual growth in 2021 was the highest ever recorded. NOAA 2024, https://gml.noaa.gov/ccgg/trends_ch4/.

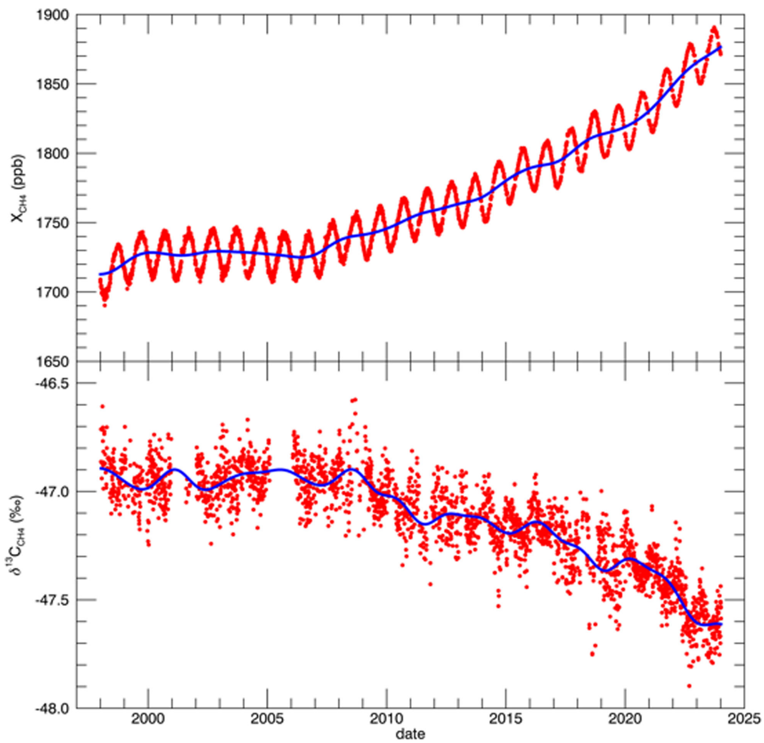

Figure 2. Top panel: methane growth as recorded at the South Pole, the world's most remote observing point. Lower panel: methane $\delta^{13}C_{CH4}$ as recorded at the South Pole, the world's most remote observing point. NOAA/CIRES 2024.

The South Pole record, which effectively integrates the evolution of the planetary atmosphere, illustrates the strong global trend since 2007 towards $\delta^{13}C_{CH4}$values more depleted in ^{13}C. This trend suggests biological emissions from wetlands, waste and agriculture are the probable dominant cause of recent growth [6–9]. Estimates imply that agriculture and waste are responsible for over 40% of total annual methane emissions worldwide [1,10].

The implications of methane's new growth are explored in figure 3, which shows the effective radiative forcing (ERF) expected for CO_2 and CH_4 if the atmosphere evolves along several shared socioeconomic pathways (SSPs) [11]. The baseline (0 line) represents the ERF expected in the Representative Concentration Pathway (RCP 2.6), compatible with the Paris

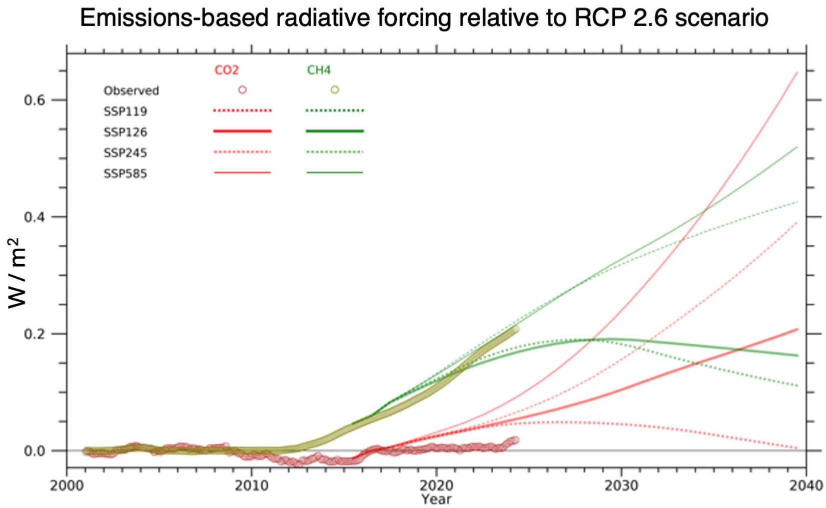

Figure 3. Effect of methane's recent growth compared with several SSP scenarios (SSPs, [11]). The current methane trajectory follows trajectories of scenarios SSP2_4.5 and SSP5_8.5 which are incompatible with the Paris agreement goals. SSP126, based on the optimistic scenario RCP 2.6 compatible with the 2°C target, assumes effective global action will limit additional forcing to 2.6 W m^{-2} by 2100.

Agreement. The SSP 1–19 (estimated warming 2081–2100 of 1.0–1.8°C) and SSP 126 paths (estimated warming 2081–2100 of 1.3–2.4°C) are 'sustainable'. In SSP 245, with estimated warming by 2081–2100 of 2.1–3.5°C, some countries make good progress while others do poorly. In the high-end scenario SSP 585, estimated warming by 2081 to 2100 is 3.3–5.7°C. Agricultural methane emissions in the three lowest SSP scenarios, including SSP 1–2.6 are shown in figure 4. The two lower scenarios are impossibly optimistic, but with determined effort something similar may be attainable by 2050.

3. The importance of agricultural emissions

Growth of agricultural emissions in recent decades has been substantial [8,9], as human populations increase and diets consume more meat and milk. Agricultural methane emissions come from many disparate sources [3,4,12]: ruminant animals; manure tanks and lagoons; biodigesters; ditches and irrigation works; inundated rice fields; and crop and animal waste fires.

In 2020, with wide uncertainties, from top-down data Saunois *et al*. [1] estimated agricultural and waste emissions of approximately 245 Tg. Their bottom-up estimates implied enteric fermentation in ruminants and emissions from manure produced approximately 117 Tg, while rice cultivation produced approximately 32 Tg and biomass and biofuel burning approximately 27 Tg. Landfill and waste deposition emits approximately a further 69 Tg yr^{-1} [1], sourced from waste food or agricultural products in addition to paper, sewage sludge and industrial biowaste, etc. In a parallel analysis of the period between 2000 and 2020, Jackson *et al*. [10] estimate annual emissions from agriculture and waste rose by approximately 33 Tg, with annual emissions from ruminants and from waste both rising by approximately 15 Tg. Regionally, in the 2000–2017 period, it is likely that agriculture and waste in South Asia and China each produced approximately 60–70 Tg yr^{-1} of methane, and approximately 15 Tg yr^{-1} came from each of the USA, Europe, South East Asia and Brazil. The rest comes from Africa, Latin America, West Asia and Australasia [13].

A separate source apportionment of food-related methane emissions, from the EDGARv7 database [14], is listed in table 1 and shown in figure 5. In the Global Methane Pledge, nations

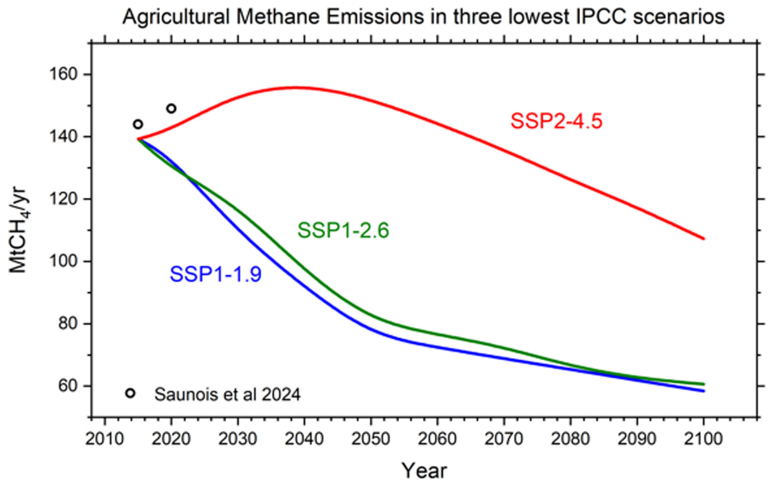

Figure 4. Evolution of total global agricultural emissions for the three lowest SSP scenarios (figures 3 and 4 calculated by M.R. Manning for this study).

Table 1. Shows percentage increases for illustrated source categories, over the half-century period 1970–2021 and the relative share of the source category to the total methane emission in 1970 and 2021, respectively, in the EDGAR inventory [14].

		enteric ferment-ation	manure management	rice cultivations	emission from biomass burning	incineration and open burning of waste	other anthropogenic sources
increase 1970–2021		+59%	+42%	−22%	+137%	+18%	+95%
relative contribution to total emission	1970	29%	3.7%	20%	0.3%	0.5%	47%
	2021	29%	3.3%	10%	0.5%	0.4%	57%

committed to cut methane emissions by 30% by 2030. More specifically, looking at methane mitigation potential in the period 2020–2050, Rogelj & Lamboll [2] considered the cuts necessary to achieve the 1.5°C warming target of the Paris Agreement. For methane, the bulk of the task would have to be in the more tractable fossil fuel sector, with a 73% cut, but agricultural emissions would have to be reduced by approximately 32%.

Is it possible to cut agricultural emissions of methane by nearly a third? Globally, such a cut in total annual agricultural and waste emissions of methane would imply reductions of approximately 75–80 Tg yr^{-1} by 2050. Apportioned by source type, such notional cuts could be distributed as 30–40 Tg yr^{-1} from livestock and manure, 5–10 Tg yr^{-1} from rice fields and over 20 Tg yr^{-1} from biodigesters and food-related waste disposal. In the atmosphere, other emissions being steady, such cuts would drop ambient methane by perhaps 25–35 ppb yr^{-1} as a very rough estimate. Including all anthropogenic sources, if a sustained annual 10 Tg yr^{-1} reduction (i.e. per year, per year) persists till 2050, implying a total 270 Tg reduction in global emission in 2050 compared with 2023, then atmospheric methane will decline to approximately 1380–1400 ppb at the end of 2050, assuming no change in methane's lifetime, and no change in natural emissions or sinks.

But reducing agricultural emissions is a very challenging task. As a specific example of the difficulty in cutting agricultural emissions, in the UK total methane emissions decreased dramatically from more than 5 Tg yr^{-1} in 1991 to approximately 2 Tg yr^{-1} in 2021 [15]. But

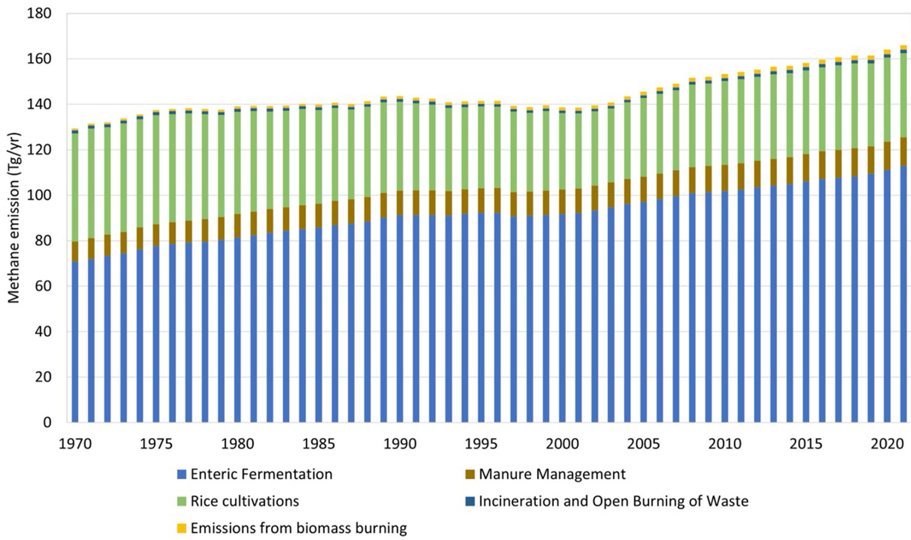

Figure 5. Source apportionment of global agricultural and waste methane emissions, estimated from the EDGARv7 database [14].

despite good progress and determined policy, UK emissions from agriculture remain stubbornly near-constant at approximately 1 Tg yr^{-1}. The cuts were primarily achieved through improvements to landfill technology [15].

4. The importance of accurate quantification

In constructing emission inventories from agricultural sources [16], so-called bottom-up emission inventories are built by classifying methane sources into source-type buckets, and then multiplying the population in each generalized-bucket by generalized emission factors for that source type. Bottom-up inventories are characteristically very precise but probably inaccurate. By contrast, top-down emissions are derived from measurements in the air above and around the sources. They can also include source partitioning evidence from isotopic measurement [17]. Top-down results are often very imprecise but more accurate for that snapshot moment—the measured methane is actually present in the air.

Many current emission inventories and regulatory processes depend on 'emission factors' to assess methane output per animal per unit time, or per kg of manure. Many factors stem from recommendations of the Intergovernmental Panel on Climate Change (IPCC) [18,19]. Emission factors inevitably are generalizations and may become outdated, inappropriate (i.e. from different circumstances or diets), or be poorly based (e.g. from very few measurements, years ago). Revisions can be substantial. As an example, revised manure-management emissions factors in the USA [20] increased the estimate of methane emission by 71.8% compared with earlier methodology [18], without evidence for substantial actual behavioural change on farms.

The IPCC defines tiered methods for compilation of emission inventories based on emission factors, which scale with improved precision at the expense (or challenge) of complexity (and data availability). Tier 1 emission factors are based on detailed assessments of the available literature (see the supplemental information in Gavrilova *et al.* [19]), but include little or no local (country-specific) activity data. Tier 2 emission factors are country-specific, including local data. Tier 2 methodology considers methane conversion yields in various ruminant types for enteric methane as well as emissions from manure [18]. The Tier 2 method is recommended particularly when enteric fermentation stands out as a significant agricultural emission source. Tier 3 includes locally sourced and activity-specific emissions factors, suitable for comprehensive national inventories and evaluating mitigation plans [21]. These methods are most effective when factors affecting emissions from both enteric fermentation and manure management are well-understood. This requires a comprehensive understanding of feeding and husbandry systems, including the precise energy conversion factors used to determine the needs of animals.

Thus, there is a danger that agricultural emissions become targeted using precise but inaccurate accounting and notional offsets such as soil removal or sequestration, rather than real, measurable, quantified reductions in emissions [22]. Flux quantification according to standardized emission factors, typically assessed without uncertainties or errors, may be 'good enough for some fluxes but not all' [23]. Regulatory policies and financial incentives or taxes that are based on standardized 'one algorithm fits all' emission factors inevitably risk rewarding bad practice and penalizing good. For example, producing the same quantity of milk by using a smaller number of larger cows may give an apparent reduction in the accounting metric even though the amount of methane emitted to the air does not change or even grows. To cite Goodhart's Law, 'Any observed statistical regularity will tend to collapse once pressure is placed upon it for control purposes' [24]. In other words, when a metric—such as a methane emission factor—becomes a target, it ceases to be a good metric. When metrics are 'gamed' they become untrustworthy: public trust evaporates.

We focus on actual measurements, not calculated metrics. It is argued in the following discussion that flux quantification by direct measurement is now both needed and feasible. Top-down measurement of the methane emitted into the air gives direct quantification of each individual emitting source, whether large or small, by measuring actual emissions from each emitting farm unit or agricultural location. Once sources are pin-pointed, action can be taken. Apart from the confidence brought by direct local measurement with known uncertainties, the co-benefit is that mitigation efforts can be targeted and focused. Emission 'hot spots' can be identified and reduction targets prioritized. The real effect of mitigation can be verified, rather than counting notional gains from manipulated emission factors.

Rapid methodological progress is being made in making measurement of both mixing ratios and isotopes easier, and in standardizing quantification. For regulators, improvement in top-down measurement makes tracking mitigation claims a much more robust process than relying on emitter-reported bottom-up data. However, to make top-down measurements feasible, costs of locating emissions and quantifying them must be kept low, especially in tropical nations, to make quantification feasible either by using simple measurement methodologies directly accessible to farmers and regulators, or else via inexpensive service provision from local agricultural-industry skill providers.

5. *In situ* source identification and emission quantification

Methane emissions can be quantified by a wide range of methods [25] covering single-source measurements, through field-scale and farm-scale determinations, to regional- and national-scale air measurements. Direct *in situ* measurement of emissions is possible using air measurement coupled with mass balance or micrometeorological methodologies to quantify fluxes. Isotopic information is also very helpful in identifying and quatifying sources [26]. *In situ* methods may lack the precision offered by placing animals in confined settings, but gain accuracy by assessing 'normal' environments.

Measurement around livestock is mainly by optical spectroscopy. Instruments are typically mobile, able to map an emission plume to part-per-billion precision [17]. For fixed locations such as rice fields, eddy covariance flux towers can be used. Typically, near-infrared lasers are used but newer mid-infrared laser systems promise better precision and useful isotopic measurement. Quantification methodology varies, from simple mass-balance calculation to complex Bayesian modelling of emission plumes. Isotopic measurement, either *in situ* by low-precision laser systems or offline by higher precision mass spectrometry is invaluable in discriminating between different sources, a common problem (e.g. a leaky biodigester next to a fossil gas installation).

Most directly, animal breath can be measured in respiration chambers or in the field using 'GreenFeed' head stalls [27]. For sources such as manure tanks or on-farm biodigesters, one-off leaks can be tracked by infrared camera. Though the detector needs to be near the emission source as leak detection limits are approximately 20 g CH_4 per hour at an imaging distance of 6 m [28], this is helpful in finding cracked pipes and manure facilities. But in the farm setting, even without an infrared camera it is relatively easy at this distance to spot a cow and prioritize the eructating rather than the flatulating emission orifice. Handheld portable laser methane detectors [29] may also help, but practical experience in Africa is not encouraging. More directly, Schokker *et al*. [30] placed infrared sensors in milking machines, to monitor cattle breath directly. This may lead to better quantification of the effects of feed intake, animal health and animal management.

The simplest local-scale approach is an inexpensive walkaround backpack survey, for example to assess a decaying cover on a landfill. Chen *et al.* [31] demonstrated this experimental methodology elegantly around the Munich Oktoberfest. Though most methane came from fossil fuel sources, such as gas appliances, in this unusual case nearly a quarter of the methane came from quaffing humans themselves. On the field to farm scale, open-path techniques [32] are well suited for continuous monitoring of large agricultural sources such as manure lagoons, biodigesters and landfills. In detecting short intense bursts (e.g. 10 min duration) that may come from a biodigester, continuous monitoring will track events and help locate them. However, it may be some years before these methods become simple to install, affordable and sufficiently accurate to be widely suitable for routine small-scale farm use.

Tracer gas release experiments, where a known quantity of a different but similar gas such as acetylene is emitted to calibrate the methane flux, can be employed to improve the accuracy of emissions estimates. Quantifying emissions from Danish cattle farms, focusing on manure tanks, Vechi & Scheutz [33] used fixed downwind sampling points coupled with controlled tracer gas releases to determine emissions with good precision. More generally, the tracer gas dispersion studies can find that emission factor methods underestimate emissions by as much as 35%.

For field- to regional-scale measurement campaigns, driving surveys are rapid, and can be inexpensive. Access is usually on public roads that require no prior permissions and can provide regulatory 'surprise', catching large and unexpected point sources of methane. Measurement of methane mixing ratios and collection of air samples for C-isotopic ratios is often coupled with measurement of associated gases such as ethane, N_2O and ammonia, coupled with meteorological sensors (temperature, wind speed and direction) and global posititioning system (GPS) positioning [17]. Measurement precision is expected to improve in the near future with techniques such as mid-infrared frequency comb systems [34] that should allow much more precise determination of C-isotopic ratios in methane.

Lowry *et al*. [17] used instruments mounted on a sport utility vehicle (SUV) for ground-based surveys in rural northern England. Plumes were found both near known agricultural sites such as cow barns and manure piles and also from unknown sites such as gas leaks. Methane C-Isotopic measurements ($\delta^{13}C_{CH4}$) were used to distinguish between biogenic and fossil fuel sources. Agricultural biogenic sources were detectable up to 500 m from cow barns and readily distinguished from nearby fossil fuel gas leaks. Similarly, Riddick *et al*. [35] surveyed an 8000 km^2 region near Denver CO, USA, that was densely studded with both agricultural operations and oil and gas installations. Compared with measurements from a decade previously, the surveys showed that oil and gas industry emissions had fallen dramatically, probably in response to regulatory changes, but agricultural emissions had changed little.

Air moves in three dimensions but simple ground-based measurements lack the third axis. Eddy covariance flux towers measure vertical turbulent fluxes and are well-suited to determine mass fluxes in settings such as rice fields where emissions are uniformly distributed over a known area. Where source distribution is complex, uncrewed aerial vehicles (UAVs or drones) allow for detection of methane at height [36]. Measurement can be either by flying lightweight (approx. 2 kg) optical instruments or by air sample collection for later off-line analysis. UAVs are very versatile and manoeuvrable, and are especially useful if also supported by on-ground instruments. Technologies are rapidly improving, including new mid-infrared laser measurement instruments, but whole air sampling is still needed for high-precision isotopic measurements of $\delta^{13}C_{CH4}$ and $\delta^{2}H_{CH4}$, especially when multiple different local source types are present.

Drones weighing 5–10 kg, especially with fixed wings, can carry high-precision cavity-based instruments reporting data in real time by radio telemetry, and are capable of ppb-level or better measurement precision. Typically, a fixed-wing UAV aircraft is used with a maximum take-off weight of approximately 7–10 kg and 20–30 min flight time. This can to map emission plumes, flying an ultra-portable analyser with a CH_4 measurement range of 0.01–100 ppm. Shah *et al*. [37] used an onboard anemometer and high-precision *in situ* analyser to quantify emissions from a dairy herd of 150 cows, while Yong *et al*. [36] used the same UAV payload to calculate whole-site emissions for a landfill, using mass-balance methods.

Airbag collection allows very inexpensive drones to be used for isotopic source-apportionment studies of small-scale agricultural emissions. One disadvantage is that each drone flight can only carry a few bags, so the upward dimension of plumes is only spot sampled. As an example of air sampling by UAV, Brownlow *et al*. [38] collected light airbags to 3000 m altitude above Ascension Island (8° S central Atlantic). High-precision lab measurement of $\delta^{13}C_{CH4}$ in the collected air allowed them isotopically to characterize methane from tropical sources in the Congo basin, Cameroon and Angola, and Brazil.

Karion *et al.* [39] and Vinkovic *et al*. [40] overcame the difficulty of collecting multiple samples by using aircore sampling. During flights they slowly collected air into a 50 m long steel coiled tube, injecting a CO marker spike at the start and end of each profile. Then, on the ground, they measured the air in the coil by flowing the air through a cavity-ring down instrument. This gave them good transects through emission plumes. Coupling aircore measurements with ground-based mobile or static *in situ* measurement and also tracer gas release provides powerful tools for accurate quantification of CH_4 emissions.

There is much opportunity for regulatory bodies to develop inexpensive monitoring systems. For example, in the jurisdictional area of a local authority such as an administrative county, small road vehicles such as double-cab farm pickups or SUVs are useful, preferably electric to avoid motor emissions while measuring. Currently most vehicle-mounted systems are operated by university teams, but these affordable systems are well suited for adoption by regulatory agencies such as local governments, or by consultancies if emission declarations become compulsory to support taxation penalties or financial rewards for emission reduction. On wider scales, UAV-mounted high-resolution remote sensing offers identification of emission hot spots in regional to national areas. As an example, a fully autonomous fixed-winged aircraft can carry a sensor load of up to 100 kg, over distances up to 1000 km [41]. Uncrewed aircraft of this sort would be ideally suited to support regulation of agricultural emissions, verifying reward- or taxation-based emission mitigation programmes.

6. Satellite measurement

Satellite observations are increasingly useful in assessing aggregate emissions on regional and national scales, for example for determining sectoral inputs and identifying regionally persistent increasing trends [42]. Although recent satellite systems provide detection thresholds for point source emissions as small as approximately 200 kg h^{-1} (e.g. GHGsat, [43]), most mapping has higher detection thresholds. Weather conditions, such as clouds, albedo and wind, also make accurate detection and quantification of emissions very challenging. For near-future satellite generations, the detection thresholds of plume fluxes will probably remain at approximately 100 kg h^{-1} or more [42], too high to assess local small-scale agricultural sources, especially in the tropics and India. Thus though useful for spotting large leaks from oil and gas installations, most current satellite-borne systems lack adequate resolution to monitor individual agricultural point sources.

Satellite monitoring can, however, be used to assess diffuse regional emissions. In a modelling study set with varying meteorological conditions in the important dairy farming region of North Island New Zealand, researchers [44] showed that methane enhancements (increment over background) between 3 and 8 ppb should be within the useful range of satellite detection and quantification. More generally, with appropriate modelling and ground-truthing, it may be possible to use satellite observation to assess emissions routinely at sub-national and ideally at sub-provincial scale [45]. Coupled with *in situ* technologies, such as mobile vehicle-mounted systems, UAVs and open-path sensing with reflectors, satellite monitoring is likely to provide affordable and effective assessment of tropical agricultural emissions.

7. Calculating emissions

Quantitative assessment of methane emissions from a localized source such as a farm or an agricultural facility needs methods similar to those used for landfills (table 3 in [46]), especially dynamic inverse modelling, based on measurements downwind of the source. Emissions are typically modelled as Gaussian plumes. Methods are varied, including mass-balance calculations, eddy covariance, gradient methods, dispersion modelling and tracer-ratio calculations [47].

In the mass-balance approach [36], inputs to a volume of air are measured by the difference in measurements upwind and downwind of the source, which enables calculation of the net surface flux emitted into that volume. Atmospheric eddy dispersion models [48] and Bayesian inversions can be used to solve the problem of quantifying sources to match methane measurements and wind data for the meteorological conditions prevailing. However, to obtain an emission rate, atmospheric enhancements in the methane mixing ratio over background need to be multiplied by wind speed. While measuring wind speed at a single point (or more) is easy, getting the wind field correct is very difficult and this directly influences the uncertainty in the emission measurement.

Open-path measurement techniques can also be used in mass-balance approaches: these measurements are made with a single fixed sensor, from which laser beams are radiated across the measurement area, and reflected from pre-positioned mirrors back to the instrument. Cossel *et al*. [32] carried out open-path measurements using mid-infrared light on multiple reflections from a UAV downwind of a known source, thereby mapping out the emission plume. After 12 flights their result was within 15% of the known flux, with a detection limit approximately equal to the methane output from approximately 25 beef cattle. However, the method is vulnerable to local meteorological fluctuations (e.g. water vapour). Future developments may include the use of a single laser and multiple reflectors mounted on small drones in 'swarm mapping' of plumes, to gain instantaneous three-dimensional (3D) maps of emission plumes.

Total emissions can usually be estimated with reasonable accuracy from SUV-mounted measurements made on surrounding roads, while on-site measurements are needed to map the spatial variability, and thus to identify specific local sources. Upwind measurements are not essential as they can be substituted by downwind measurements of the background outside the plume. This may be helpful in agricultural sites where access may be partial.

However, much work is needed to reduce flux uncertainty, including better meteorological control and better methane isotope measurement. There is still far to go before standardized and transparent methodologies are generally accepted for regulating emissions. Thus, there is need for development of standardized methodologies for plume detection and quantification of emission rates from the methane measurements and local meteorology, in software packages that are easily accessible by emitters and regulators, and usable by both two-dimensional (2D) on-ground vehicle-mounted measurement teams and also by those who have the additional ability to deploy UAV-mounted measurement for 3D quantification.

8. Emission hot spots 1: biomass digesters

Agricultural methane sources on any farm are not evenly distributed: there will be extreme local hot spots such as farm manure tanks, or crop-waste fires, and wide areas of scattered small sources, such as grazing cows [47]. Anaerobic biodigesters, in which manure and other organic waste can be converted to methane-rich biogas, are increasingly widespread, especially in European farms and urban waste treatment facilities. In well-contained biodigester systems with strong membrane covers, the methane leakage is small. But biodigesters can be very leaky and their emissions may be rising rapidly [49,50]. In Denmark, Fredenslund *et al*. [51] measured methane losses from 69 biogas plants representing approximately 50% of Danish production, determining an emission factor of 2.5% for the Danish national inventory.

Using an SUV-mounted instrument package, Bakkaloglu *et al*. [49] used repeat passes through emission plumes to estimate total emissions of methane from 10 biodigester plants of varying sizes, six of which were farm-based. For these 10 plants, the average emission rate was approximately 16 kg CH_4 h^{-1}, and the average loss was nearly 4% of production. Bakkaloglu *et al*. [49] found that, in general, methane emission rates from smaller farm biogas plants were higher than from larger food waste biogas plants. Bakkaloglu *et al*. [50] compiled all mobile studies and assessed the biogas and biomethane supply chain emissions. They found that emissions in UK plants could range from as low as 1.7% to as high as 12.7% of total gas production, with an average of 5.2%. The wide ranges in emissions sharply demonstrate the large opportunities for mitigation.

Hot spot emissions from biodigesters may be transient, not continuous. But most discovery methods—UAV, SUV mobile lab, etc., provide only snapshots in time and may not accurately assess total emissions. It may be necessary around large facilities to set up continuous measurement via 24/7 methane analysers or eddy covariance flux towers. Measurement would be inaccurate and subject to flux divergence with local meteorological variations, but would provide warning of unexpected venting. If for example a spike in methane emission is recorded at dawn on a very cold day, then the alerted SUV or UAV patrol could return, to search for the source. As a simpler rule of thumb for small-scale farm installations, human nose detection of associated gases such as ammonia and H_2S is effective: 'if it smells it probably leaks methane too'. Biomass digester hot spots offer obvious primary targets: they are accessible, easily controlled, and once identified, emissions can quickly be reduced.

9. Emission hot spots 2: manure management

As Lord de Ramsay observed '*Semper in excretia sumus solim profundum variat*' (We're always in the manure; only the depth varies) [4.15 pm, https://publications.parliament.uk/pa/ld199798/ldhansrd/vo980121/text/80121-06.htm].

Manure tanks and lagoons are excellent habitats for strictly anaerobic methanogens and hence important methane emitters [11]. In the UK industry, in 2021, the NAEI [15] bottom-up inventory reports 153 kt of methane from manure, 613 kt from waste, and 841 kt from enteric fermentation. Eliminating manure emissions would cut 15% of agricultural non-waste methane emissions, or 7% from the national total from all sources, approximately 2 Tg in 2021.

In figure 6, a medium-sized UK dairy farm was mapped by a SUV-mounted instrument package supplemented by walk-around surveys. The farm has 350 adult cows and the same number of calves. An 8 million litre manure lagoon (figure 7) was on the north-east corner of the site. The mapping used GPS equipped vehicle-mounted measurement of CH_4, CO_2, $\delta^{13}C_{CH4}$, together with backpack-carried walk-around measurement of CH_4 and CO_2,

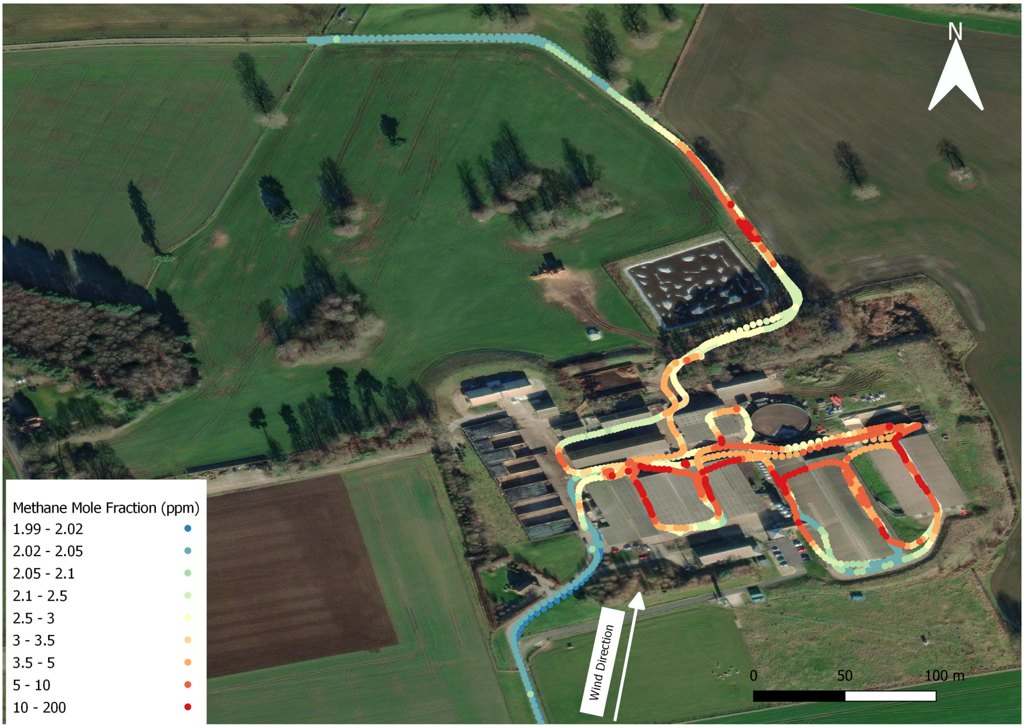

Figure 6. Mapping a UK dairy farm for methane emissions. Wind from south-south west (lower left). Air around large cow-filled barns in lower centre of map has very high methane. Large manure holding lagoon of figure 7, covered by membrane and water also has high values. Note scale bar (100 m). (study by A Alshalan).

Figure 7. Slurry tank (left) and lagoon containing approximately 8 million litres of manure (right), UK dairy farm. Manure lagoon is covered by white geomembrane liner cover, with vents. Rainwater has accumulated over the canopy. Large upward bulges (whales) may be lifted up by underlying volumes of methane.

supplemented by bag sampling for offline high-precision $\delta^{13}C_{CH4}$ by mass spectrometry. The wind was from the south-south-west. The problems are obvious from the map (figure 6) with high methane mixing ratios both around the cattle barns and downwind from the lagoon. Methane emissions from typical UK manure lagoons such as this are up to tens of kg h^{-1} (Lowry, unpubl.). Tighter covering and better gas capture could reduce farm emissions substantially.

In California's highly intensive dairy industry in 2021 (1.7 million dairy cattle), inventory estimates are that manure produced 54% of emissions while enteric fermentation was responsible for approximately 46% of methane emissions [52]. California has an ambitious target for 2030 of reducing dairy and livestock emissions by 40%, compared with 2013 [53]. Proportionate to production, Chinese manure emissions are probably lower than for North America [54],

Figure 8. Field burning (left) and crop-waste fires (right), dry season in northern hemisphere Uganda. FAAM aircraft MOYA flights Jan 2019, photograph: D. Pasternak.

but China's dairy industry is also intensive and manure accumulation is a major problem [55], suggesting similar ratios.

Once discovered, strongly emitting sources are tractable to emission reduction. Physical methods include using slurry covers and solid–liquid separation. Acidification of slurry to pH 5.5 sharply reduces methane emission, in some cases by over 90% [56]. Antimicrobial agents help [56], but indiscriminate use of antimicrobials leads to development of resistant strains, and may be a source of microbial resistance in hospitals.

Composting, which is aerobic decomposition of organic waste, may have lower climate effect compared with anaerobic digestion, if leak rates are low. The co-benefit is inexpensive locally sourced fertilizer. However, methane emission can occur during the composting process. In California, Vergara *et al*. [57] conducted continuous measurements of greenhouse gas emissions from a large manure composting plant. Total methane emitted was 1.7 ± 0.32 g of methane per kilogram of feedstock. They recommended managing oxygen levels to minimize methanogenesis, and focusing on the first composting weeks to minimize methane emissions.

Pig and chicken manure is another major agricultural source of methane emission in China, Europe and the USA. In sub-Saharan Africa it is likely that communally farmed pigs produce very much less methane per pig than intensively farmed densely housed pigs in the US and Europe [58]. In the UK also, many pigs are kept outdoors or on straw-based systems, and pig muck is sold in exchange for straw bedding for the pigs. By contrast, in Denmark methane emissions rates up to 14 kg h^{-1} were measured from 10 outdoor manure tanks with highest rates during summer and autumn [59]. Dalby *et al*. [60] investigated the effect of reducing slurry retention time inside Danish pig houses and found that more frequent clean-outs to outside storage dramatically cut emissions, and reduce the development of microbial resistance to antibiotics, thus cutting antibiotic use. Mitigation technologies include manure acidification, biogasification or anaerobic digestion and gas collection, combined with flaring or microbial biofiltration.

10. Emission hot spots 3: crop waste and grass fires

Worldwide, the production of crop waste is immense (61). Bottom-up estimates suggest crop waste, stubble and dry grass burning (figure 8) annually produce approximately 17 Tg of methane globally, and biofuel fires add approximately another 10 Tg [1]. Stubble and waste fires (figure 8) are widespread in India [62], S.E. Asia and sub-Saharan Africa [63]. Seasonal deliberate or neglectful grass-burning is extremely widespread, especially in Africa. Fires burn incompletely, producing a complex mix of gases, including CO and CH_4 and a thick smoke of aerosols and pollutants.

In Africa, Bauer *et al*. [64] estimate biomass burning annually causes 43 000 premature deaths from air pollution. Moreover, soil nutrients are carried up into smoke and eventually rain out into the ocean. Yet, much crop waste has the potential to be used as animal feed, or as feedstock for biodigesters, or to be composted together with manure, generating a fertilizer or beneficial soil amendment, improving circularity, with co-benefits including more productive animals [65]. On upland soils, fire suppression would allow tree regrowth and support methane uptake by woody surfaces [66].

In the UK, uncontrolled burning was ended by the 1993 Crop Residues (Burning) Regulations. Similar bans extend across much of Europe [67]. Much waste is now incinerated in high-temperature controlled settings for electricity, emitting CO_2 but little methane. In India, with some of Earth's most polluted skies, bioenergy and biogas production are alternatives. The technological and investment demands of ending burning are not challenging, and would have potent co-benefits by cutting air pollution and improving public health.

11. Rice fields

Wetland rice fields are inundated, leading to anoxic conditions in the mud, with methane production. Currently, methane emissions from rice fields are probably stable or declining [68], although rice cultivation is increasing in Africa. But global emissions from rice remain large, approximately 29 Tg annually [1]. Emission fluxes from wet-grown rice vary according to crop stage, so sustained (whole season) emissions measurement can be carried out by small eddy covariance flux towers erected beside representative paddy fields.

Before 1980 nutrient inputs to rice paddies came from organic matter, which led to extremely high methane emissions. Emissions have been reduced by the increasing use of fertilizer replacing the organic inputs [69]; however, manufacture of nitrogen fertilizer is very energy-demanding, and causes emission of CO_2 and methane. Fertilizer application may also increase N_2O and NH_3 emission. Qian *et al*. [70] advocate a variety of mitigation interventions including better straw removal, non-continuous flooding and new rice variety selection. Tillage in the winter dry season may help cut methane emissions without diminishing yields [71]. Overall, Zhou *et al*. [68] identified water management techniques, off-season straw return and straw to biochar, as capable of delivering 22–28% reduction of emissions.

12. Burning, converting, or destroying agricultural methane

Methane oxidation, by bacterial methanotrophy or in oxidation via thermocatalysis with heat recapture, removes most global warming effect. Burning agriculturally sourced methane to CO_2 produces energy (usually as electricity). Electricity generation from bio-methane and agricultural waste can add a valuable night-time supplement to village solar power systems.

Methane's flammability limits in air [72] are approximately 5–15% at room temperature, with the lower limit in hot fires dropping to approximately 3% at 600°C. For UK farm waste, Foster *et al*. [73] estimated large-scale use of anaerobic digesters with electricity generation on farms could generate 1.6 TWh of electricity, 0.5% of the UK's annual demand [74].

Manure biogas is a viable fuel for agricultural tractors (Owczuk *et al*. [75]). But this is only useful in climate terms if biodigester and power generation systems are rigorously leak-free, with NO_x emissions also controlled. Direct methane-to-methanol conversion is possible, as is pyrolysis to hydrogen [76], while biodigestate can be converted to methanol [77]. If this could be achieved commercially at low energy cost, it could serve as the basis for liquid fuels [78], perhaps including synthetic aviation fuel, which would be transformative in controlling aircraft emissions.

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In ambient air in barns and milking sheds, methane in the air may be as high as 35–100 ppm (own team observations). Near the cow's nose, air can be in the range 0.05–0.2% methane [79]. This methane can be oxidized in hot air (approximately 500 to 700°C) over a catalyst [80]. Thus, though it consumes energy, in certain settings it may be feasible simply to destroy methane in ambient barn air by oxidation to CO_2, which destroys 97% of methane's 100 yr global warming power [81].

Direct methane destruction is only beneficial in climate-warming terms if its energy cost is less than the marginal effect of making that energy in the 'worst' (most climate-warming) supply in the local energy grid. Nisbet-Jones *et al*. [81] found that to remove methane from 1 m^3 of air with 100 ppm methane, the maximum energy use permissible was 0.55 kWh if the energy came from wind farms, but no more than 0.012 kWh for gas-powered electricity or 0.007 kWh if the energy came from coal. In the early hours of windy winter nights, the UK price of electricity is often negative. In these circumstances, using 2 am surplus wind-power to destroy methane in the air of cattle barns may become attractive. However, any allocations of cheap night-time electricity for methane destruction are probably soon to compete with rapidly rising demand from cryptocurrency and artificial intelligence servers.

Alternatively, methane removal in bioreactors containing methanotrophic bacteria [82,83] is an attractive option, as is encouraging uptake from soil and trees [66] This costs little energy but unfortunately methanotrophy is very slow for mixing ratios found in cattle barns. Nevertheless, it is possible that effective bioremoval methanotrophs can be found.

13. Feed additives

Various feed strategies have been proposed to reduce methane emissions from ruminants [84, 85,86]. These can inhibit methanogenesis by suppressing methyl-coenzyme M reductase, or in the case of nitrate additives, compete with methanogens for hydrogen. Rumen-modifying additives, such as some plant compounds, alter the conditions in the rumen that support methanogenesis.

But many methane mitigation ideas have only been trialled at research scale and do not consider the practical differences that would be encountered in production systems at farm scales [87], especially in lower-income nations. Reviewing the evidence, Hegarty *et al*. [88] report that only by two feed additives, 3-Nitrooxypropanol and dried *Asparagopsis* (red algae, seaweed), delivered over 20% mitigation of enteric methane routinely, the evidence for the efficacy of 3-Nitrooxypropanol being stronger. Bromoform, one of the main active compounds within the methane reducing seaweeds, can be produced synthetically.

Some government agencies, including in the USA, have approved 3-Nitrooxypropanol (https://www.edf.org/media/fda-paves-way-reducing-methane-emissions-livestock). However, for many reasons [87], there has been limited adoption by commercial farmers, especially those with extensive pasture-based systems. Whole-farm assessment of interventions is needed because mitigating single-cow emissions may even increase total climate-warming effects from the entire food-production chain. Moreover, dietary management approaches are broadly unaffordable in low- and middle-income nations for whom methane reduction targets may prove difficult [89]. However, research efforts to identify and develop cheaper and more broadly applicable enteric methane mitigation interventions are increasing, including even anti-methanogen vaccines.

The option of semaglutide additives for humans is considered in §18.

14. Alternative approaches for methane mitigation: disease control, breeding and good farm management

An obvious and inexpensive way to cut methane emissions from dairy cattle and sheep is to eliminate common diseases. A small healthy herd can produce as much food as a much larger unhealthy herd. In Ethiopia, measures to reduce Trypanosomiasis can reduce emissions intensity by up to 36%, and in Tanzania, East Coast Fever vaccination could reduce emissions intensity by up to 29% [90].

Bovine mastitis, an inflammatory bacterial infection of the udder may cost 11–18% of gross margin in intensive dairy farms [91]. It is prevalent in cattle that are intensively reared, and is spread among animals lying on wet manure-ridden bedding, despite widespread antibiotic prophylaxis. It is less common in pasture-raised cattle. In New Zealand, where grass-fed cattle are the norm, good animal management has significantly reduced mastitis [92]. 'De-intensifying' dairy farming would generally cut mastitis and reduce antibiotic use. On sheep farms, intensive rearing systems are linked to increased lamb mortality (which can be 10%), which can be cut by simple measures such as better hygiene [93], reducing the number of ewes and hence emissions.

Breeding may help. In the Dutch dairy industry, a 24% reduction in methane emission may be possible by 2050, through breeding low-methane animals [94]. In sheep, positive traits from selecting for low-methane ewes include improved wool yield and lean tissue [95]. Barriers to realizing the potential of low-methane genetics include the lack of market incentive, and costs of phenotyping animals in sufficient quantity to build a selection index. However, owing to the strategy's permanent benefits, implementing a low-methane breeding programme could be a cost effective strategy to reduce methane, both for intensive and extensive systems.

More generally, locally specific knowledge, resources and breeds can do much to mitigate emissions by better farm management. Studying small dairies in west Java, Indonesia, de Vries *et al*. [96] identified small-scale changes (e.g. in use of rice straw) that had significant effect on emissions per litre of milk. In Brazil, silvo-pastoral systems using alien Australian eucalypts and African signal grass can support carbon neutral milk production [97], and there may be a case for using local grasses and legume trees. Using legumes also reduces the need for energy-intensive nitrogen fertilizers.

15. Open range versus intensive livestock management

The problem of comparing emissions from intensive versus extensive dairy systems is challenging [47]. In most western countries (especially California) and in China, intensive dairy production is widespread, driven by political and 'efficiency' factors [98]. Note, however, that on animal welfare grounds, there is substantial and growing market pressure in Europe and North America in favour of grass-fed dairy products.

Intuitively, grass-fed dairy or open-field pigs and chickens, with manure falling in open pastures, should produce less methane than intensive systems of confined animals where manure is collected and stored. In open pastures, manure is quickly aerobic as it is aerated by immediate contact with air. Thus the habitat for anaerobic methanogens is much more limited than in anaerobic manure lagoons. But the evidence is ambiguous. In pastures, the effectiveness of on-soil oxidation depends on the intensity of manure fall and the moisture content. Where stocking rates of animals per hectare are low, and manure falling on pastures is rapidly aerobic, soil methanotrophs can be nourished by nutrients from manure, so the soil methane sink can be enhanced, reducing fertilizer-linked climate effects.

In a whole-farm model study of eight farms, Rotz *et al*. [99] found that all-grass dairy systems typically have lower milk productivity than intensive systems and may have higher methane emissions per unit of milk, while the system that supplemented grass with grain had

Figure 9. Sampling for $\delta^{13}C_{CH4}$ source signatures in methane emitted by goats and sheep in an overnight 'boma' (corral made with thorny branches), Kenya, 2020.

much lower losses and emissions than all-grass systems. However, in grass-fed systems input costs are lower. Rotz *et al.* [99] found that the all-grass systems gave greater profitability per unit of land. Comparing seven model scenarios, Reinemann *et al.* [100] found the lowest net greenhouse gas emissions per unit of milk occurred in a scenario with a confined herd and an anaerobic biodigester producing electricity. Otherwise, greenhouse gas emissions were lower in grazing scenarios with feed supplementation. In the Italian Alps, Zanon *et al.* [101] found an extensive production system produced less methane per cow per day compared with intensive production, but per kilogram of milk, the intensive scenario produced less methane. Normalized per litre of milk, the question of comparing emissions from intensive versus extensive dairy systems remains open. It needs study by direct *in situ* measurement on real farms.

In North America, the UK and in Europe, subsidy-driven solar panel farms are replacing both pastures and prime arable land. In a UK government report, [102] Waygood noted the conflict this caused between food production and climate change mitigation, and found that no modelled scenario delivered a strong cut in greenhouse gas emissions without also causing large reductions in food supply. That would require a change in diet and perhaps obesity prevalence (discussed further in §18 below). There has been little full-system analysis of the net climate benefit of energy production from converted farmland in preference to using parking lots and warehouse roofs, given the loss of food production in northern nations and consequent greenhouse gas emissions caused by importing food, probably from increased conversion of tropical land such as Brazil's savanna.

Beef cattle are usually raised in whole or in part on pasture. In Africa beef cattle are typically owned by small-scale farmers, grazing on dry pastures or crop residues in harvested fields. Tropical pasture soils are methane sinks, especially in the dry season [103]. On these soils, with aerobic manure decay, methane emissions will be limited (the senior author, who is Zimbabwean, recalls using cowpats as childhood frisbees). However, cattle are often kept in overnight enclosures 'bomas' (figure 9) where anaerobic conditions occur in urine-soaked manure, producing methane [104]. In parts of central Africa, cattle are treated as wealth and are unproductive. Here the transition to electronic currency via mobile-phone services may reduce such unproductive cattle populations. In India, where many male cattle are similarly unproductive, the popularity of sexed semen in the dairy industry may bring emissions reduction and improve animal welfare.

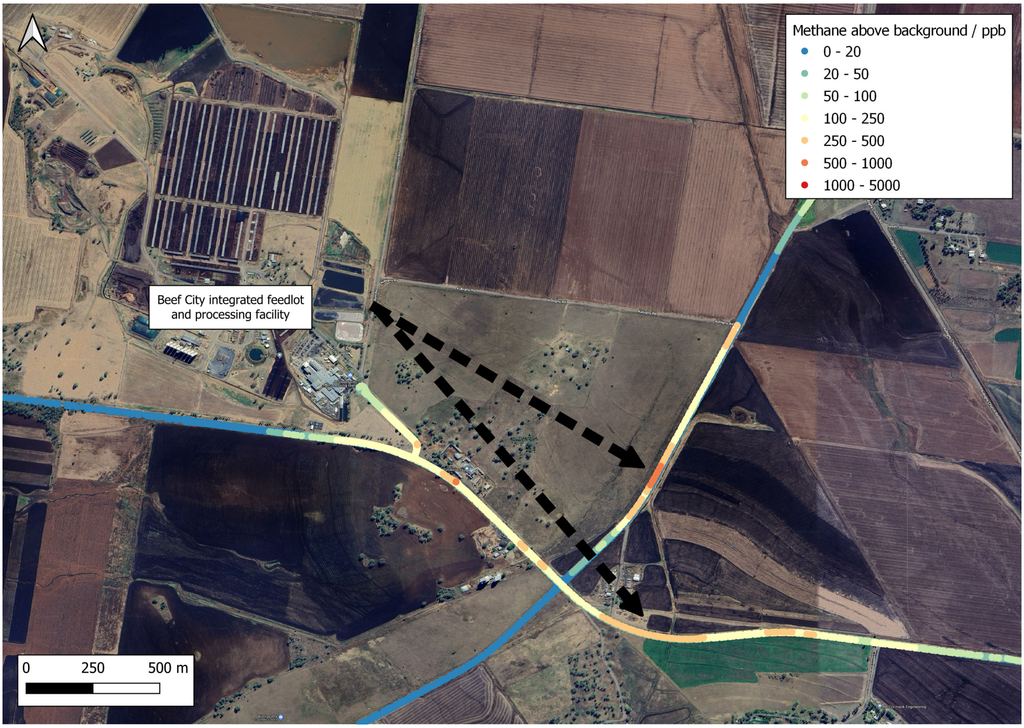

Figure 10. Methane emissions from Beef City, a large cattle feed lot in Queensland Australia. Note, on the road the extremely high methane enhancements, with the increment in the plume peaking over 1 ppm above background, more than 1 km from the feedlot.

In the USA, nearly half of all beef produced comes from operations with less than 100 head of cattle [105]. But concentrated animal feeding operations are widespread in the USA, Australia and parts of South America, where very large beef feedlots can have tens of thousands of animals. These hot spots have high methane emissions. An example is Beef City, Purrawunda, Australia (figure 10). This is over 800 ha in area with a capacity of 26 500 animals. High methane mixing ratios in ambient air immediately downwind of such feedlots, as well as over manure stores, offer potential direct mitigation targets, for example by catalytic methane destruction powered by solar electricity.

Other ruminants such as sheep, goats and camels are also important methane emitters in Africa [106], the Middle East, in Muslim countries where pork is not eaten and in countries such as New Zealand that are well suited to sheep farming. In the steppe grasslands of China, stocked by one sheep per hectare per year, Tang *et al.* [107] estimated methane's soil sink in pastures was equal to half the methane emission from enteric fermentation and manure; at a stocking rate of four sheep per hectare per year, 20% of the methane was taken up.

From Brazil and Australia, large-scale live animal shipping has developed to the Middle East [108], with some ships carrying up to 20 000 tightly confined animals. Livestock carriers have poor safety records and animal welfare is deeply troubling. Odour is significant (e.g. https://www.bbc.co.uk/news/world-africa-68342054) and methane emissions on the long voyages are probably large. New Zealand banned this trade in 2023. The simplest immediate way for Australia and Brazil to cut methane emissions is to end long-distance exports of live cattle and sheep for slaughter and instead to ship the meat chilled or frozen.

16. Nitrous oxide: interaction between methane and N_2O mitigation

Agricultural emissions of nitrous oxide are closely linked to methane emissions, and measures to mitigate methane need to consider effects on nitrous oxide emissions, which in some cases may increase [109,110]. Nitrous oxide is discussed at further length in the electronic supplementary material (SM 1).

17. Landfills

Landfills, which also include paper waste, industrial biowaste and sometimes sewage sludge, are not the primary focus of this review, but there is much in common between mitigating emissions from urban landfills, farm waste and agricultural hot spots such as biodigesters. Food waste ends up in landfills, which produce annual global methane emissions of approximately 71 Tg yr^{-1}, or 18–19% of total anthropogenic emissions [1]. The exponential growth of huge and poorly managed tropical landfills urgently needs to be managed [25]. India's urban landfills are very large and are obvious mitigation targets. In Africa large landfills are high emitters; they frequently burn (emitting air pollution), and can have catastrophic landslides (e.g. [111]). Moreover, landfills range from mega-city mountains to village dumps and on-farm heaps: technology that works on a large scale can often be adapted to serve micro-installations.

Large landfill emitters, with plumes of hundreds of kg h^{-1} or more, are readily observed by satellite [42]. Identifying and mitigating these emissions should be a high global priority, especially in tropical countries with very rapidly growing mega-cities. Landfill methane abatement technologies include gas collection and energy recovery or flaring, implementation of biocovers/filters and optimized microbial methane oxidation.

The UK sharply cut its methane emissions by focusing on landfill and waste [15], with little political debate. The cost was small. Banning disposal of biowaste in landfills has been an efficient strategy in several EU countries. Similar reductions can be achieved globally, with wide co-benefits to public health. Mitigating landfill emissions is not complex, nor are the technical demands challenging. At a minimum, covering with a metre of soil provides habitat for methanotrophs that can consume much of the methane emission. Slightly more sophisticated methods include geomembrane covers and piping to extract gas, which is then burned to generate electricity, thereby funding the work.

18. Human diet and health

Reducing obesity and increasing plant-based human nutrition will probably cut methane emissions, both from agriculture and landfills, provided crop waste and fertilizer are well managed. Global over-consumption of food (the 'obesity epidemic') is damaging to public health [112]. Both obesity and airborne particulates (from crop-waste burning) are major causes of illness [113]. These factors are increasingly important in Africa, the Middle East and South Asia [114].

There are counter-tensions: nutrient deficiency is widespread [115] and animal inputs are widely important in essential micronutrients. Desmond *et al.* [116] point to the potential complications of exclusively plant-based (non-dairy) vegan diets, with significant risks such as stunted growth unless nutrient intakes are carefully managed. For example China's 5-year plans focused on increasing intensive milk production and consumption, bringing about remarkable benefits in nutrition and growth [117], though with major environmental effects [118]. Reducing local ruminant emissions in one country could have the unintended consequence of increasing dairy and meat imports from other countries, potentially with larger net global warming effect. Land use changes such as afforestation or rewilding for overall carbon mitigation may alienate

Table 2. Mitigation targets and methods.

mitigation focus	detection, quantification, verification	target mixing ratio	reduction or removal methods	other options	cost of reduction or removal
manure stores	24/7 instruments	100–1000 ppm	thermocatalytic oxidation; bio methanotrophy	use of methane as fuel	moderate, e.g. using landfill technology
in-building methane	24/7 instruments	~100 ppm	thermocatalytic oxidation; bio methanotrophy	biomethanotrophy in linked greenhouses	moderate if solar/wind powered
biogas system leaks	24/7 instruments	<10 ppm	rigorous control of leaks; gas tight covers on tanks	use of methane as fuel	low or profitable
in pasture methane emission	*in situ* CH_4,$\delta^{13}C_{CH4}$ measurement : UAV, SUV	100 ppb enhancement over background	better pasture management, animal health, feed additives	biomethanotrophy	moderate for feed additives
livestock—low CH_4 breeding	*in situ* proof of emission reduction	100 ppb enhancement	herd breeding and management	hippophagy, vegetarian	low
rice field emission	*in situ* CH_4,$\delta^{13}C_{CH4}$ measurement , UAV, SUV	100 ppb enhancement	better crop management	biomethanotrophy	moderate
crop-waste smoke	UAV, SUV, satellite	100 ppb enhancement	alternative waste use—e.g. energy		low to moderate

pasturelands and rough grazing, and inadvertently increase emissions from intensive dairy farming.

Tropical livestock are primarily pastoral, raised on land that is marginal or unsuitable for arable agriculture [65]. Technologies that triumph in Texas may struggle in South Sudan. Both in India and Africa cattle have immense cultural or religious importance [119]. Usufruct (communal) livestock grazing over extensive areas of open pasture widely supports low-income human populations. In many semi-arid areas, animals browse trees and bushes where crops cannot grow. In South Asia lacto-vegetarian products are vital for food supply, while in many African nations oxen play a major role as draught animals for ploughing and transport.

Compared with pre-human Africa, in parts of West and South sub-equatorial Africa, the past replacement of natural methane-productive wild antelope and buffalo ruminant fauna by the modern cattle monocultures may have caused a decline in total herbivore methane production ([120]: their Fig. 5a), except in Uganda, Ethiopia and the Sahel where cattle dominance probably increased emissions. Even in North America, where the historic herds of more than 50 million bison were nearly eliminated by European settlers, the relative change in ruminant methane emissions today compared with pre-colonial times may represent a more moderate increase than is traditionally considered [121].

Recently, semaglutide medication, either injected or given orally, has become widely used for weight management or weight loss. It is too early to assess the potential effect on methane

Table 3. Detection and quantification: local area methane measurement methods.

source	detection systems and precision required	point source detection ranges kg hr^{-1}	access and timescale	cost of detection and quantification
manure lagoons and tanks	static 24/7 laser analysers. < 1 ppb CH_4, cameras for spot leaks.	0.1 upwards. 0.02 at <10 m	good access 24/7 monitoring	relatively low, for installing and maintaining analysers
in-building: cow barns, etc.	static 24/7 laser analysers <1 ppb CH_4, multi airlines	0.1 upwards	good access 24/7 monitoring	installing and maintaining analysers
biogas systems and digesters	static 24/7 systems cameras for spot leaks	0.1 upwards. 0.02 at <10 m	good access 24/7 monitoring	installing and maintaining analysers
outdoor feedlot	static instruments; eddy covariance towers, UAV patrols	0.1 upwards	good access 24/7 monitoring	installing and maintaining systems
animal and in-field measures of methane emission from livestock	greenfeed devices or SF6 tracer halters. Field campaign measurement by UAVs, SUV, and tracer gas emission, etc., < 1 ppb CH_4	0.1 to 28 and upwards	variable; UAV access over grazed pasture. Seasonal diurnal campaigns	moderate to high: skilled staff and campaign costs for mobile labs
rice field	static eddy covariance flux towers. Drones, SUVs, <1 ppb CH_4.	0.1 and upwards	access may be difficult; UAVs can quantify plumes	moderate/high: SUV field campaigns and fixed towers
crop-waste fires	plume quantification, <1 ppb satellite studies of regional enhancements	0.1 upwards	SUV and UAV light aircraft. seasonal	moderate/high: SUV and UAV skills and access costs. High satellite costs.
landfills	downwind plume measurement, <1 ppb satellites for large landfills	0.1 kg h^{-1} and upwards satellites approximately 200 kg h^{-1}	SUV and UAV. Satellites: global scope	moderate SUV costs. High costs in satellite work.

emission from food production, but given the global scale of the obesity epidemic, the reduction in demand may become significant.

To this end, though there are no simple global solutions, nor common global diets, the United Nations and its affiliated agencies such as the Food and Agriculture, World Health and World Meteorological Organisations have become adept at localizing global targets and methods; rather than applying Eurocentric or American lenses [65].

Table 4. Mitigation options.

target	mechanism	probable cost	potential mitigation	possible Timescale
biodigesters	leak reduction	low	some Tg yr^{-1}	rapid
manure tanks and lagoons	emission reduction	low	some Tg yr^{-1}	rapid
methane removal from ambient air in closed facilities	thermo or bio catalysis for >100 ppm air	moderate	some Tg yr^{-1}	decadal
crop-waste fires and tropical grass burning	regulatory control, alternative management	negative: major co-benefits to air quality	? > 10 Tg yr^{-1}	decadal
rice fields	management changes	low	? ~10 Tg yr^{-1}	decadal
feed additives	lower emissions	moderate/high	? 1–10 Tg yr^{-1}	decadal
better animal management	disease reduction, low-methane breeds	low	? ~10 Tg yr^{-1}	rapid
landfills	leak reduction and capture	low	>> 10 Tg yr^{-1}	rapid to decadal
Human Dietary change; obesity reduction	lower ruminant populations	low	>> 10 Tg yr^{-1}	decadal

'?' signifies a guess.

19. Practical targets

To mitigate agricultural emissions there are many attractive targets (table 2). These include emissions from manure, leaks from biogas systems, using waste gas for fuels both directly for tractors on-farm, or via conversion to methanol and hence liquid fuels and even synthetic aviation fuel. Improved management strategies, low-methane animal breeding, and methanogenesis inhibitors could significantly reduce emissions. With favourable energy supplies, methane removal is possible. Marginal abatement costs of tractable emissions from manure, biodigesters and crop waste, are likely to be comparable with mitigation costs for gas and landfill industry emissions. In practical terms, as illustrated by the proposed US EMIT LESS Act (https://www.congress.gov/bill/118th-congress/senate-bill/4056/text), regulatory carrots (subsidies) are more likely to succeed than sticks (penalties).

Such measures would need to be accompanied by determined efforts to improve monitoring worldwide. Rather than inaccurate bottom-up estimates, sustained direct top-down measurements are globally needed to locate, characterize by source type, and quantify emissions accurately. Mobile and UAV measurements are now becoming more widespread in China, but needs in much of the tropics (table 3) include SUV measurement platforms helped by UAVs over major emitters such as dairies and landfills.

In India, Africa and South America where sources are diverse and widely distributed, sustained wide-range SUV and UAV measurement is essential. In Africa, where human populations are still growing very rapidly, especially in cities, and food demand is increasing fast, rapid and popular mitigation of crop-waste fires may be possible, for instance by encouraging more efficient energy-generating incineration with better combustion, low methane emission and control on air pollutants in smoke. Emissions from small-scale ruminant agriculture can be reduced by improved pastures and better cattle management. In the long run, better women's education, health, pensions and prosperity can reduce the main driving factor, human population growth. In India, with a lacto-vegetarian plurality, reducing emissions from ruminants is challenging. India urgently needs to reduce crop-waste burning [122], cutting both methane emissions and air pollution. Kumari *et al*. [123] conclude it may be possible to develop effective mitigation strategies, for India, despite cost and implementation barriers. By cuts both to coal and agricultural/waste emissions, India should be able to fulfil the Global Methane Pledge, with much benefit to itself.

Höglund-Isaksson *et al*. [124] examined the reductions in emissions that are technically feasible by the year 2050 (i.e. practicable but not necessarily politically acceptable). While they concluded pig manure emissions could be cut by over 40%, and methane emissions from farm waste burning could be eliminated, they were pessimistic about cattle—suggesting that dairy emissions could only be cut by 11%, while beef farming emissions might be cut by 16%.

In §3, it was estimated that cutting total global agricultural emissions by a third would demand reductions of approximately 75 Tg yr^{-1}, apportioned as 30–40 Tg yr^{-1} from livestock, 5–10 Tg yr^{-1} from rice fields, and over 20 Tg yr^{-1} from waste. In this decade, with sharp focus on hot spots such as manure stores and biodigesters in North America, East Asia and Europe, as well as crop-waste fires in India, a 30 Tg yr^{-1} reduction may be feasible. In the longer term, Duan *et al*. [125] very optimistically suggest China's agricultural methane emissions could be cut by 90% (or over 20 Tg) by the year 2060. Added to this could be sharper percentage cuts in emissions from landfills (globally perhaps up to 50 Tg reduction by 2050), which are arguably the most attractive immediate target for emission reduction. Though cutting total anthropogenic emissions in the year 2050 by 270 Tg compared to 2023 (see §3) is probably unrealistic, a more modest reduction in total anthropogenic emissions (agriculture + landfills + fossil fuels) of up to 100 Tg yr^{-1} is imaginable by 2050, which could lead to a drop of several hundred ppb in ambient methane.

20. Conclusions

In the context of efforts to reduce both long-term effects of CO_2 and near-term forcing by methane, controlling agricultural emissions of methane should be an urgent part of national commitments to limit climate warming. Many actions to cut methane emissions have strong co-benefits for public health. The costs of mitigation are hard to assess as there is wide opportunity for technical improvement to cut costs dramatically. Though agricultural methane emissions are widely seen as intractable, much can be done to make them tractable.

Effective mitigation of agricultural methane emissions will need determined policy attention coupled with sustained implementation of that policy, but may not necessarily be expensive. Efforts to reduce emissions will be encouraged if cutting measured methane emission is seen as important in nationally determined contributions to climate mitigation. The alternative, compensating for methane emissions by CO_2 removal is unrealistic [126] and seems wrong intuitively. It is far better to cut methane emission. The gases are very different in their radiative forcing timeframes, and balancing the forcing from a small mass of methane would mean removing a much larger mass of CO_2.

Broad tasks include: (i) better measurement: identification, location, and quantification of emissions; (ii) emission reduction: cutting or stopping emissions; (iii) methane destruction/removal, and use to produce energy, where emission reduction is not feasible; (iv) human diet changes.

(1) *Measurement*. In the near future, with better top-down measurement and cheaper UAVs, it should be widely possible to replace bottom-up emission factors by more accurate quantification by direct measurement. Tasks are location, quantification, isotopic/trace gas identification of different sources (often multiply co-located). Data gaps are wide [127] but measurement methods have improved dramatically over the past decade. Key measurement needs are mobile (SUV) 2D mapping, UAVs (including heavy drones for 3D

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measurement and mid-infrared sensors) and more widespread measurements of isotopes and associated gases. Modelling skills, including freely accessible standardized software packages, need to be developed conjointly, for rapid quantification over both point source plumes and disseminated sources. Given the importance of agriculture, and with the increasing availability of SUV and UAV measurement systems, usefully accurate *in situ* top-down evaluation of emissions is now well within the resources of most tropical nations. Globally, capacity-building is needed, to provide the skills and equipment to carry out measurements and to translate those measurements into accurate, detailed inventories.

(2) *Emission Reduction* is the least-cost choice; the opportunities are listed in table 4. The most obvious immediate targets are cutting leaks from biodigesters and biogas chains [50], and also from manure tanks, ponds and lagoons (cattle, pigs, chickens). Substantial emission reductions may be possible through better farm management, with disease reduction, producing the same amount of food from fewer but healthier animals. The use of low-methane ruminant breeds, as well as the use of feed additives should also help. Ending crop-waste fires and use of crop waste as fodder or for energy generation from waste biomass can help reduce emissions by tens of Tg yr^{-1} globally. In Africa and Asia, crop-waste fires and landfills urgently need to be tackled, not just because they make methane, but also because of the damage their air pollution does to human health. In rice fields, changes to water management, tillage and waste handling will cut emissions. Saunois *et al.* [1] assessed enteric fermentation and manure emissions in 2020 as 114–124 Tg yr^{-1}, and rice cultivation emissions of approximately 32 Tg yr^{-1}, with total agricultural emissions of approximately 147 Tg yr^{-1}. It is difficult to assess the potential global effect of mitigation measures, especially with a moving target as the use of biodigesters grows, but together with better livestock management and breeding, reductions of 30–40 Tg yr^{-1} may be feasible for low or moderate cost. Cutting crop waste and grass burning, and mitigation of specifically agricultural waste heaps may deliver another 20 Tg yr^{-1}, and better management of rice cultivation 10 Tg yr^{-1}. Such reductions are merely guesses, but collectively over the period to 2050 it is possible that determined regulatory intervention may lead to total a worldwide reduction of agricultural emissions by perhaps 50–60 Tg yr^{-1} or more.

(3) *Destruction*. Methane oxidation to CO_2 removes most global warming effects [81]. In high-methane air in closed cattle facilities such as cattle barns, where mixing ratios are high (50–100 ppm), methane destruction may be feasible. Food waste in landfills can be managed, with leak reduction and methane capture to generate electricity. In particular, in the tropics, electricity generation from bio-methane and agricultural waste can potentially add a valuable night-time supplement to village solar power systems. In some settings, conversion of biomethane to methanol may be feasible with new catalysts.

(4) *Human diet changes*. On a wider scale, considering human rather than cattle feed, evidence-based changes to human diet, for example encouraging better public health by cutting obesity, will reduce per capita food consumption and hence both agricultural production and landfill inputs. The benefits through cutting methane emission may be substantial, but cultural priorities need consideration too, especially in lacto-vegetarian communities, and in cattle-dependent sub-Saharan Africa.

The real test for greenhouse gas policy is direct atmospheric measurement (figure 1). When a multi-year section (say 5 years) of the methane growth curve (figure 2) has entered a convex decline, and when the $\delta^{13}C_{CH4}$ curve reflects a cessation of inputs from the gas, oil and coal industries, and also an end to growth in total biological emissions (both anthropogenic and natural), then there will be hope for abatement of methane's climate disruption.

The task of reducing agricultural methane emissions is complex and challenging. There are no magic bullets. But rapid real reductions, though difficult, are both necessary and possible.

Data accessibility. Supplementary material is available online [128].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. E.G.N.: conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing—original draft, writing—review and editing; M.R.M.: conceptualization, formal analysis, investigation, methodology, software, validation, visualization, writing—original draft, writing—review and editing; D.L.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing—original draft, writing—review and editing; R.E.F.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing—original draft, writing—review and editing; X.L.L.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, validation, visualization, writing—original draft, writing—review and editing; S.E.M.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, validation, visualization, writing—original draft, writing—review and editing; J.L.F.: conceptualization, data curation, formal analysis, investigation, methodology, software, supervision, validation, visualization, writing—original draft, writing—review and editing; R.E.R.N.: conceptualization, data curation, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing—original draft, writing—review and editing; S.B.: data curation, formal analysis, investigation, methodology, software, validation, visualization, writing—original draft, writing—review and editing; S.M.L.: conceptualization, data curation, investigation, methodology, resources, validation, visualization, writing—original draft, writing—review and editing; C.B.: conceptualization, investigation, methodology, writing—review and editing; T.R.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing—original draft, writing—review and editing; G.A.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing—original draft, writing—review and editing; H.A.C.DvdG.: conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing—original draft, writing—review and editing; L.M.: conceptualization, funding acquisition, investigation, methodology, project administration, supervision, validation, visualization, writing—original draft, writing—review and editing; C.S.: conceptualization, formal analysis, investigation, methodology, writing—original draft, writing—review and editing; C.W.M.: data curation, formal analysis, investigation, methodology, validation, visualization, writing—original draft, writing—review and editing; P.B.R.N.-J.: conceptualization, formal analysis, investigation, methodology, supervision, validation, visualization, writing—original draft, writing—review and editing; A.A.: conceptualization, data curation, investigation, methodology, validation, visualization, writing—original draft, writing—review and editing; J.M.F.: data curation, investigation, methodology, software, validation, visualization, writing—original draft, writing—review and editing; E.J.D.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing—original draft, writing—review and editing.

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