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Challenges And Prospects: Reducing U.s. Methane Emissions Via Red Macroalgae (asparagopsis Taxiformis) Feed Additives To Inhibit Enteric Methane Production From Ruminant Livestock

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ABSTRACT

Approximately 27% of U.S. methane emissions are emitted by the agriculture sector annually, primarily by ruminant livestock as a GHG *enteric fermentation* bi-product (EPA, 2022). This proposed intervention explores the feasibility of scaling up use of anti-methanogenic ruminant feed additives, to directly reduce U.S. agricultural methane emissions at the source. A careful review of in vitro, in vivo and small-scale pilot studies revealed that the potent, anti-methanogenic bioactive compounds in red macroalgae (Asparagopsis Taxiformis) can both safely and effectively inhibit methanogenesis during enteric fermentation, resulting in up to 90% reduction in methane emissions without adverse risk or consequence to animal health, productivity or enteric fermentation efficiency (Kinley et al, 2016; Machado et al, 2016; Mernit, 2018; Chagas et al, 2019; Vijn et al, 2020; Min et al, 2021; Symbrosia, 2022). Next, nuanced feasibility challenges and prospects to scaling up this intervention are explored, including how to optimize consistency in production feed additive quality and quantity, how to optimize market and industry acceptance at scale, and establishing the role of the U.S. government in large-scale implementation. Finally, short-term, mid-term and long-term policy options and recommendations are explored, to determine the best next steps forward to enhance success of this intervention upon implementation. Study conclusions illustrate that assuming adequate resources and intervention compliance upon implementation, the widespread A. taxiformis feed additives in the U.S. livestock sector at scale has considerable potential to achieve substantial reductions in enteric methane emissions.

KEY WORDS: health policy, enteric fermentation, greenhouse gas emissions, methane, anthropogenic, climate change, public health, agriculture, livestock

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I. INTRODUCTION AND BACKGROUND

i. OVERVIEW OF KEY GREENHOUSE GAS (GHG) EMISSIONS AND ENVIRONMENTAL CONSEQUENCES OF GLOBAL CLIMATE CHANGE

Since the advent of the Industrial Revolution in the mid-1700s, greenhouse gas (GHG) emissions from the burning of fossil fuels for carbon-producing human activities have contributed to and ultimately caused global climate change. Carbon dioxide, the most commonly emitted anthropogenic GHG, accounts for 79% of emissions each year. Other GHGs contributing to the ongoing climate crisis include methane (16% of emissions), nitrous oxide (6% of emissions) and fluorinated gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6), which collectively account for the remaining 2% of global GHG emissions (EPA, 2022).

Anthropogenic GHGs continuously trap heat in the atmosphere, leading to a rise in average global temperatures. Over time, increasing global warming levels induce more frequent and more destructive weather events worldwide, including cyclones, hurricanes, drought, wildfires, flash floods and severe precipitation (Climate Watch, 2022), among other devastating ecosystem impacts. The latest Intergovernmental Panel on Climate Change (IPCC) Report confirms if rising average global temperatures exceed 2°C from pre-industrial levels, environmental damage may become irreversible, and Earth's fragile ecosystems may eventually lack capacity to sustain life (IPCC, 2022). Unless and until GHG emissions are substantially reduced, and rising average global temperatures are capped well below 2°C, deleterious destruction to global ecosystems is an absolute certainty in the coming decades (Wuebbles, 2017). Today's decisions by the international community, to either act on or ignore our collective, catastrophic reality, will ultimately determine the magnitude and severity of future climate change impacts.

ii. SIGNIFICANCE OF REDUCING U.S. METHANE EMISSIONS

Anthropogenic GHG emissions all contribute to and cause climate change and global warming, in trapping heat in the atmosphere for extended periods. However, the degree and capacity to which GHG emissions can exacerbate climate change processes varies dramatically. Generalizable *carbon dioxide equivalent* (CO2e) values are used to account for these differences and to facilitate clear comparisons of projected impacts. CO2e values are broadly calculated by multiplying the quantity of GHG emissions in tons, by the GHG's 100-year *Global Warming Potential* (GWP) relative to the impact of one ton of CO_2 emissions, where GWP reflects the net effect of GHG energy absorption capacity and GHG efficacy in trapping atmospheric radiation in the long-term (Ritchie, 2020).

GHGs with low GWP values like carbon dioxide (1 GWP over 100 years) are less effective in trapping atmospheric radiation and have lower capacity for energy absorption, and as such, indicate a lesser degree of climate change impacts. Comparatively, GHGs with higher GWP values like methane (25-36 GWP over 100 years) are much more effective at trapping atmospheric radiation and have higher capacity for energy absorption, and as such, indicate a greater degree climate change impacts in the long-term (EPA, 2022). In other words, a ton of methane emitted today will have approximately 80 times the global warming impact as a ton of carbon dioxide emitted over the next 20 years (EDF, 2022). Hence, although carbon dioxide comprises the vast majority of annual GHG emissions worldwide, methane emissions have far greater potential to hasten the rate of global warming and environmental dysfunction (Denchak, 2018). As such, targeting reductions in U.S. methane emission to efficiently slow the rate of global warming will be the overarching focus of this proposal.

In 2020, U.S. methane emissions accounted for 11% of total annual U.S. GHG emissions. Approximately 27% of U.S. methane is produced by the agriculture sector, which accounts for the second largest source of U.S. methane emissions. Agricultural methane is perpetually emitted by ruminant livestock as a GHG bi-product of *enteric fermentation,* a normal digestive processes that breaks down food in the rumen (first stomach) of ruminant livestock such as beef cattle (EPA, 2022). This intervention will specifically target reductions in enteric methane emitted by ruminant livestock.

iii. THE U.S. FEDERAL SUSTAINABILITY PLAN AND INTERNATIONAL AGREEMENTS TO REDUCE U.S. METHANE EMISSIONS

The U.S. is the world's second largest contributor of GHG emissions (Climate Watch, 2022), and until recent years had yet to formally commit to any serious reductions in U.S. GHG emissions. In December 2015, nearly 200 Parties at U.N. COP21 signed and adopted the landmark *Paris Agreement*. This momentous, legally-binding treaty united the international community for the first time under an ambitious, common cause: to limit the rise in average global temperatures to well below 2°C compared to pre-industrial temperatures, or else face irreversible climate catastrophe (UNFCCC, 2022). The U.S., however, did not become a signatory to the Paris Agreement until April 2016, under the Obama Administration. The U.S. was also the first Party to formally withdraw from the Paris Agreement in 2020 under the Trump administration, but soon rejoined the agreement in 2021 under the Biden Administration (Barboza, 2021). Nonetheless, since resigning the U.S. to the Paris Agreement, the Administration has been keen to make up for lost time, committing the U.S. to historic, ambitious reductions in GHG emissions, and encouraging the world to follow its lead in transitioning to zero-emissions alternatives.

In September 2021, President Biden announced a partnership with the European Union (EU), challenging nations worldwide to join the *Global Methane Pledge* and commit to global methane reductions of 30% of 2020 levels by 2030. The EU-U.S. partnership was formally announced in November 2021 at U.N. COP26, as a key component of the groundbreaking *Glasgow Climate Pact*, to restrengthen global climate commitments and maintain rising average global temperatures below 2°C. Signatories pledged to (1) halt and reverse deforestation, (2) speed up the transition to electric vehicles, and (3) reduce methane emissions. Importantly, this agreement also includes the first ever negotiated references to phase down coal power and cease fossil fuel subsidies. Finally, Parties at COP26 finalized *The Paris Rulebook*, which clarified remaining implementation logistics for the Paris Agreement. By the conclusion of COP26, 196 Parties including the U.S. signed onto the Glasgow Climate Pact. Additionally, over 100 Parties committed to substantial methane reductions under the *Global Methane Pledge*, accounting for 46% of global methane emissions and over 70% of global GDP (UNFCCC, 2021).

At the national level, President Biden announced *The Federal Sustainability Plan* via *Executive Order 14057* in November 2021. In line with U.S. COP26 commitments per the Global Methane Pledge, this historic executive order formally established some of the world's most ambitious national-level climate goals, including: (1) cutting annual GHG emissions 50% by 2030, (2) reaching 100% carbon-pollution free electricity by 2035, and (3) achieving a net-zero emissions economy by 2050 (CEQ, 2021). Of particular interest to this proposal, President Biden also announced the *U.S. Methane Emissions Reduction Action Plan*, which details opportunities to sustainably reduce U.S. methane emissions and "boost American-competitiveness" in the coming decade. The action plan briefly references opportunities to expand U.S. biofuel production to replace fossil fuels, though no concrete pathways forward are described (WHDCP, 2021). Intervention aims to target reductions in U.S. methane emissions are thus in direct alignment with the Biden Administration climate goals and national strategy.

iv. PUBLIC HEALTH BENEFITS OF REDUCED METHANE EMISSIONS

Anthropogenic methane emissions pose serious public health risks and harms, especially among vulnerable populations and communities at disproportionate risk for exposure to negative public health implications associated with global climate change (Climate Watch, 2022). Depending on the level and duration of exposure, methane emissions can cause and exacerbate multiple health conditions, such as respiratory diseases (e.g. asthma, lung cancer, COPD), neurological problems, reproductive health problems, as well as developmental issues in children (EPA, 2022). Further, methane is a precursor to ground-level ozone, an air pollutant that accumulates in the troposphere and causes other serious health problems. Depending on the level and duration of exposure, tropospheric ozone can cause and exacerbate multiple health problems such as coughing, chest pain, worsening of lung disease and reduced lung function. In the long-term, prolonged exposure to ground-level ozone can also lead to permanent lung scarring, which can severely inhibit proper lung functioning (EPA, 2021).

Reductions in U.S. methane emissions would lessen the negative public health implications of climate change, while lessening the risk for developing or exacerbating serious health complications. Reductions in U.S. methane emissions would therefore benefit public health in the short-term and long-term, by decreasing the risk of prolonged exposure to toxic GHG pollutants. Ultimately, the greater the reduction of methane emissions, the greater the magnitude of positive public health implications in the future.

II. INTERVENTION PROPOSAL AND JUSTIFICATION

i. REDUCING U.S. AGRICULTURAL METHANE EMISSIONS USING ANTI-METHANOGENIC RUMINANT LIVESTOCK FEED ADDITIVES

Several peer-reviewed studies have explored anti-methanogenic properties of various species of macroalgae, both in in vivo and in vitro settings. Each species of macroalgae contains a unique combination of bioactive compounds with varying degrees of anti-methanogenic potency and long-term efficacy (Kinley et al, 2016). Researchers are particularly enthusiastic about the red macroalgae species, Asparagopsis Taxiformis (A. taxiformis), and its promising potential for use as an anti-methanogenic ruminant feed additive, to reduce enteric methane emissions at the source. When supplemented in ruminant livestock feed as a feed additive at low levels of inclusion (<1—2% dry matter intake (DMI) of ruminant's diet), the potent bioactive compounds in A. taxiformis are consistently shown to both safely and effectively inhibit methanogenesis during enteric fermentation, resulting in up to 90% reduction in methane emissions from studied livestock, without adverse risk or consequence to animal health, productivity or enteric fermentation efficiency (Kinley et al, 2016; Li et al, 2016; Machado et al, 2016; Mernit, 2018; Chagas et al, 2019; Roque, Salwen et al, 2019; Roque, Brooke et al, 2019; Vijn et al, 2020; Kinley et al, 2020; Min et al, 2021; Roque et al, 2021).

Furthermore, A. taxiformis is completely safe for human consumption. Native to several countries including the U.S., A. taxiformis macroalgae is commonly cultivated for *limu*, an edible seaweed dish popular in Hawaiian cuisine (Abbott, 1978). Macroalgae dietary supplements have also been widely sold in health food stores for years, touted for its substantial nutritional benefits and other potent, health-promoting properties (Biris-Dorhoi et al, 2020). The next section of this proposal delves deeper into the scientific evidence justifying support for wider implementation of this intervention.

ii. SCIENTIFIC JUSTIFICATION: REVIEW OF IN VITRO AND IN VIVO STUDY FINDINGS

Several in vitro peer-reviewed studies have already explored the potent, anti-methanogenic properties of A. taxiformis, for use as a ruminant livestock feed additive to inhibit enteric methane production. One Australian study sought to identify the optimal dietary dose needed to effectively and consistently decrease methane production, while minimizing adverse risk to ruminant health and fermentation efficiency. Research consistently confirms that supplementation of A. taxiformis at low levels of inclusion (<1—2 DMI of ruminant's diet), can reduce methane production by as much as 99%, without risk to animal health, productivity, or rumen fermentation efficiency (Machado et al, 2016). Another Australian study used in vitro fermentation with rumen inoculum, to explore the anti-methanogenic effects of A. taxiformis in a laboratory setting. Research findings again indicated that A. taxiformis feed additives can safely inhibit methanogenesis in ruminants, without adverse impacts to animal health, wellbeing or metabolic productivity (Kinley et al, 2016). A Swedish study conducted in 2019 further substantiated these findings, and confirmed that potent bioactive compounds found in A. taxiformis, dibromochloromethane and bromoform, do not induce adverse animal health effects, and are safe for ruminant livestock consumption to effectively inhibit methanogenesis during enteric fermentation

(Chagas et al, 2019). Research conclusions from in vivo studies overwhelmingly support the safety and efficacy of A. taxiformis in reducing enteric methane.

Multiple in vivo peer-reviewed studies have also explored the anti-methanogenic effects of A. taxiformis feed additives on ruminant methane emissions. One Australian study found that significant, ongoing reductions in enteric methane production using A. taxiformis dietary supplements are optimized in conjunction with a high fiber diet (Li et al, 2016). Another Australian study, conducted in 2020, investigated the direct effects of A. taxiformis dietary supplements on feedlot beef cattle. Research findings confirmed that dietary supplements effectively inhibited methane production, without negatively impacts for daily livestock feed intake or to healthy rumen functioning. Further, after cessation of data collection, when researchers prepared and tasted the beef carcass, they reported no detectable changes to meat quality or taste (Kinley et al, 2020). Finally, a 2021 study conducted on beef cattle in California found that daily supplementation of A. taxiformis continuously, safely and effectively reduced enteric methane emissions for the entire 21-week study duration (Roque et al, 2021). Results from in vitro study data further support the efficacy and safety of A. taxiformis anti-methanogenic ruminant feed additives, to reduce enteric methane emissions without harm to ruminant health.

iii. SMALL-SCALE PILOT STUDIES PROVE A. TAXIFORMIS RUMINANT FEED ADDITIVES EFFECTIVELY INHIBIT METHANOGENESIS AND SAFELY REDUCE ENTERIC METHANE

Small-scale pilot studies have since expanded upon in vivo and in vitro research findings. Of particular note, the innovative CleanTech startup *Symbrosia* pioneered and conducted the world's first commercial A. taxiformis trial in 2020, to explore the large-scale anti-methanogenic effects of A. taxiformis ruminant feed additives on local Hawaiian livestock. Pilot research findings showed over a 75% reduction in enteric methane emissions, without adverse ruminant health effects in the short-term. Researchers also discovered no significant increase in bromoform residues, in testing both the ruminant meat and milk products. Additionally, feed additives were not found to significantly impact volatile fatty acid concentrations in the short-term, which are traditional biomarkers indicating animal productivity and rumen fermentation efficiency. Ruminant health biomarkers reveal animal health is not compromised by the short-term use of A. taxiformis ruminant feed additives (Symbrosia, 2021). Pilot data also points to the potential of scaling up and expanding this intervention, to achieve even larger reductions in enteric methane production from the U.S. agriculture sector.

Since this pilot study, Symbrosia has achieved further breakthrough innovations in scaling local, sustainable production and cultivation of A. taxiformis used for SeaGraze™, the startup's proprietary, low cost, anti-methanogenic feed additive. SeaGraze™ has been proven safe and effective in reducing small-scale enteric methane emissions. Research indicates that ruminant livestock diets comprised of "just a sprinkle" of SeaGraze™ daily (0.20% DMI of ruminant's diet), can result in over 90% reductions of enteric methane emissions. The red macroalgae produced for SeaGraze™ is grown sustainably in Hawaii using innovative, regenerative aquaculture technology, that uses bio-mediated seawater waste from fish farms, rather than fresh water. Additionally, to produce SeaGraze™ feed additives, the startup uses 100% renewable energy to carefully dry the A. taxiformis and enhance preservation of bioactive compounds, maximizing the anti-methanogenic effects of the feed additive when ingested. Symbrosia has even begun partnering locally with livestock farmers in Hawaii, encouraging the small-scale trial use of SeaGraze™ to accelerate local reductions of enteric methane. (Symbrosia, 2022).

Findings from small-scale partnerships point to the future efficacy of intervention compliance at the local level. Ongoing, pioneering research conducted by Symbrosia also serves as an excellent framework to build upon, in considering the potential feasibility of scaling up this intervention to the U.S. livestock sector. Given adequate resources, and assuming appropriate intervention compliance, national implementation of A. taxiformis feed additives in the U.S. livestock sector have considerable potential to achieve substantial reductions in enteric methane emissions at scale. Consistent with in vivo and in vitro study findings, Symbrosia reports that significant barriers to market entry remain in the large-scale implementation of A. taxiformis ruminant feed additives, particularly in adequately scaling up production and development (Symbrosia, 2022). The next section of this proposal explores nuanced, multifaceted considerations that must be addressed before feasibly scaling up this intervention, including a discussion of challenges, barriers, opportunities and potential prospects.

III. INTERVENTION FEASIBILITY, CHALLENGES AND PROSPECTS

i. SCOPING BARRIERS TO LAUNCH AND POTENTIAL SOLUTIONS

Research conclusions gleaned from in vitro, in vivo and small-scale pilot studies overwhelmingly point to the safety, efficacy and high anti-methanogenic potency of A. taxiformis ruminant feed additives for small-scale intervention implementation. To enhance large-scale intervention success at the national level, the following nuanced challenges, barriers and prospects must first be carefully considered:

The first challenge is how to optimize consistency in the cultivation and production quality of A. taxiformis macroalgae, and of A. taxiformis feed additives at scale. Optimizing consistent quality of A. taxiformis cultivation and production will be fundamental to achieving anticipated reductions in enteric methane, upon scaling up this intervention. Inconsistent A. taxiformis quality reduces the anti-methanogenic potency and effects of the feed additive, resulting in far fewer reductions to enteric methane (Roque et al, 2021). Inconsistent feed additive quality also implies that substantial, long-term enteric methane reductions at scale are less feasible. Further, inconsistent feed additive quality implicates an unreasonably high burden on livestock farmers, who would need to adjust daily feed additive inclusion levels per the alleged potency of the bioactive compounds, making anticipated reductions in enteric methane extremely challenging to control or project (Ridoutt et al, 2022). In considering the widespread adoption of this intervention at scale, complex implementation requirements would substantially disincentivize large-scale intervention adoption and compliance, especially among smaller-scale livestock farms with far less capacity for adequate implementation. Finally, achieving consistent, high quality A. taxiformis through optimized cultivation and production processes will be essential to persuading prospective investors and stakeholders of the financial success of scaling up this intervention in the long-term, such that the long-term net benefits of investment outweigh net costs (Kinley et al, 2020).

For instance, the macroalgae used for SeaGraze™ is cultivated using regenerative aquaculture technology that employs bio-mediated seawater waste from fish farms. Feed additives are produced using 100% renewable energy, to carefully dry and preserve the bioactive compounds and maximize feed additive anti-methanogenic effects upon ruminant ingestion (Symbrosia, 2022). To enhance consistency in the production quality of A. taxiformis at scale, evidence-based methods employed by Symbrosia to cultivate and produce SeaGraze™ could be adapted and piloted in future A. taxiformis field research, to inform setting-specific solutions in solving and cultivation quality challenges. For example, individualized, setting-specific aquaculture techniques could be developed to address unique local cultivation challenges, to achieve more consistent, higher quality A. taxiformis production at scale (Roque et al, 2021). Similarly, Symbrosia's feed additive processing techniques could likely be augmented to enhance the long-term stability of feed additive bioactive compounds. Enhancing bioactive compound stability will be essential to maximizing shelf-life, and to enhancing consistency in long-term, anti-methanogenic potency of feed additives at scale (Vijn et al, 2020; Roque et al, 2021).

Relatedly, the second (and perhaps most significant challenge in expanding this intervention), is how to optimize consistency in the cultivation and production quantity of A. taxiformis macroalgae, and of A. taxiformis feed additives at scale. Optimizing consistent quantity of A. taxiformis cultivation and production at scale will be fundamental to achieving more concrete, projected reductions in enteric methane emissions. Inconsistent A. taxiformis supply would reduce anti-methanogenic feed additive efficacy, resulting in far fewer reductions of enteric methane (Roque et al, 2021). Inconsistent feed additive quantity also implies that substantial reductions in enteric methane emissions at scale would be far less feasible. At present, large-scale algae farms in the U.S. have the capacity to produce up to 60 metric tons of dry algae biomass annually per hectare (White, 2021). In scaling up this intervention, researchers note current U.S. seaweed production capacity would need to markedly increase, to feasibly achieve success upon large-scale implementation (Vijn et al, 2020). Findings from in vivo, in vitro and pilot study findings all report significant barriers to market entry in scaling up the necessary quantity of A. taxiformis production needed to achieve reductions in enteric methane (Kinley et al, 2016; Li et al, 2016; Machado et al, 2016; Mernit, 2018; Chagas et al, 2019; Roque, Salwen et al, 2019; Roque, Brooke et al, 2019; Vijn et al, 2020; Kinley et al, 2020; Symbrosia, 2021; Min et al, 2021; Roque et al, 2021; Symbrosia, 2022).

Globally, over 25 million tons of seaweed (wet matter) are produced each year, and indeed global interest in macroalgae is increasing in its potential for use as a sustainable biofuel (Mayo-Ramsay, 2021). In considering the widescale production of A. taxiformis for ruminant feed additives, however, it is highly unlikely that market incentives alone would be sufficient to establish consistent, large-scale production of A. taxiformis in the private sector. As such, optimizing consistency in the production quantity of A. taxiformis may necessitate U.S. federal partnerships with countries like Australia, that have previously expressed specific, serious interest in scaling up production of A. taxiformis (Kelly, 2020). Enhanced research capacity would also allow the U.S. to conduct further research on remaining questions of the long-term, anti-methanogenic effects of A. taxiformis ruminant feed additives at scale.

The third challenge is how to optimize market and consumer acceptance of this intervention, upon implementation at scale. Optimizing consumer acceptance and enhancing demand for “low-methane beef” will be fundamental to augmenting market success in the long-term, and to achieving substantial reductions in U.S. enteric methane emissions at scale. Understanding nuanced consumer perspectives prior to large-scale implementation will be pertinent to enhancing acceptance of macroalgae livestock feed additives and of “low methane beef” upon market entry. Understanding consumer insights will also be crucial to enhancing precision of projection of consumer willingness to pay, for “low methane beef” meat and dairy product alternatives (Vijn et al, 2020). Such insights could inform thoughtful market pricing considerations, aimed at maximizing cost-effectiveness and affordability of low-methane alternatives to further boost acceptance.

Targeted consumer insights could be obtained directly via focus groups, to identify strategies of persuasion likely to optimize the long-term success of this new market intervention. For instance, perhaps the most effective consumer marketing strategies emphasize uncompromised taste and quality of “low methane beef”, or how access to “low methane beef” alternatives enables consumers to incrementally buy into sustainable lifestyles, without necessitating significant lifestyle or dietary changes. Relatedly, there exists substantial potential to leverage shifting market demand preference for sustainable alternatives, in appealing to increased consumer demand for participation in sustainable economies (Vijn et al, 2020). Assuming consumer marketing campaigns are successful in encouraging the widespread market acceptance of “low methane beef” alternatives, consumer buying power could be sufficient to sustain industry demand in the long-term. In the event of inadequate market approval however, the U.S. government would need to formally intervene, to enhance consumer acceptance of “low methane beef” alternatives, to address outstanding barriers to successful, sustainable market entry in the long-term,

The fourth challenge is how to optimize meat and dairy industry acceptance and compliance of this intervention at scale. Optimizing widespread meat and dairy industry acceptance in scaling up this intervention will be fundamental to augmenting long-term intervention success, and to achieving anticipated reductions in U.S. enteric methane production. First and foremost, industry compliance with this intervention does not require reductions in the production quantity of meat or dairy, and therefore would not necessarily negatively impact industry profit margins. Rather, “low methane beef” alternatives offer a creative solution to achieving indirect reductions in U.S. enteric methane, by implicating the livestock sector as part of the solution rather than the problem, and without necessitating reduced industry livestock production. Undoubtedly, current per capita animal product consumption in the U.S. is wholly unsustainable in the long-term (Oreskes, 2022). As such, industry acceptance of this innovative, sustainable intervention would signal to consumers that the industry is beginning to embrace sustainable food production, which would further incentivize consumer market buy-in. As such, it is also in the industry’s best financial interest to persuade consumer acceptance and sway widespread buy-in of this intervention.

In addressing barriers to widespread industry compliance upon implementation, it may be helpful to first incrementally introduce and pilot this intervention in smaller-scale feedlot settings, where farmers have daily contact with livestock and a high degree of control over feed intake (Ridoutt et al, 2022). Once intervention efficacy and safety can be firmly established in smaller-scale U.S. feedlots, the intervention is much more likely to be adopted at scale by U.S. livestock farmers. In the event of inadequate industry compliance upon implementation, the U.S. government may need to formally intervene to address outstanding barriers to sustained industry compliance, or to enforce implementation, to achieve long-term, sustainable reductions in U.S. enteric methane emissions. The nuanced role of U.S. government regulation is further explored below.

Finally, the fifth challenge is determining the role of the U.S. government in regulating and enforcing implementation of this intervention at scale. Leveraging federal regulation processes to optimize production efficiency, as opposed to working against established regulatory entities, will be crucial to augmenting long-term industry success in achieving reduced U.S. enteric methane emissions at scale. Historically, U.S. food production has been heavily regulated by both state and federal agencies. State-level regulatory agencies primarily collaborate with federal agencies to oversee food production within their respective states. At the federal level, the *U.S. Department of Agriculture (USDA)* and *Food Safety and Inspection Service (FSIS)* regulate meat and poultry production, while the *U.S. Food and Drug Administration (FDA)* regulates other food production processes (FDA, 2020; Saxowsky, n.d.). Relevant to this proposal, ruminant feed additives would be subject to federal regulation by the *FDA Center for Veterinary Medicine*, and “low methane” animal products would be subject to USDA federal regulation. Said state and federal agencies should be implicated as key proposal stakeholders throughout strategic decision-making processes to expand intervention implementation, to ensure complex industry requirements are met prior to scaling up at the national level. Close collaboration with U.S. food regulatory agencies would also serve to optimize the long-term, sustainable reduction of enteric methane at scale. Further, ongoing partnerships with U.S. regulatory agency stakeholders will be crucial to begin shifting and accepting ownership of the onus for intervention success, on behalf of the U.S. government. Indeed, it would be in the government’s best interest to invest time and resources in an intervention that would successfully achieve desired aims.

ii. SCOPING CHALLENGES AND BARRIERS TO SUSTAINABILITY OF INVESTMENTS AND PROSPECTIVE SOLUTIONS

Beyond barriers to launch, there remain challenges in how to incentivize the long-term sustainability of research and development (R&D) financing and investment, in scaling A. taxiformis production. Optimizing sustainable financing capacity at the state and federal levels will be paramount to maximizing market success in the long-term, and to achieving projected reductions in enteric methane emissions at scale. Of particular interest to this proposal, the U.S. *Farm Bill* expanded eligibility of USDA resources in 2018, to finance strategic expansion of algae production R&D, with the goal of increasing algae biomass cultivation yield and anti-methanogenic potency at scale (USDA, 2018). Several federal agencies, including the National Oceanic and Atmospheric Administration (NOAA), have also since expanded financing for algae R&D (NOAA, 2020). Further, federal algae R&D financing initiatives closely align with U.S. climate goals and national strategies established under the Biden Administration (CEQ, 2021). Thus, current financing available for algae R&D could be leveraged to optimize intervention efficacy at scale. Relatedly, enhancing government ownership and accountability for intervention success could further incentivize strong federal support and funding, to further enhance implementation capacity and efficacy.

In the short-term, private R&D investment has been sufficient to fund successful, small-scale research and pilot studies. Study conclusions have also all conclusively pointed to feasibility in scaling up this intervention, assuming complex barriers to launch are adequately addressed (Roque et al, 2020; Symbrosia, 2022). Additionally, corporate investment in A. taxiformis R&D is very limited at present, due to insufficient scientific evidence of the prospects, risks and benefits of implementing “seaweed-based feed ingredients" at scale (Vijn et al, 2020). Unclear proposal benefits thus discourage corporate investment, presenting significant barriers to market entry at scale. To address this barrier to entry in the short term, government subsidies may be warranted to encourage ongoing R&D in the private sector, to answer pending questions and concerns from investors. Then, once sufficient scientific evidence warrant approval from corporate investors, large-scale production funding could commence. If the intervention is proven to safely and effectively reduce enteric methane, additional stakeholder support and investment could be encouraged. In considering long-term, sustainable financing opportunities to scale up this initiative, it will also be imperative to actively recruit stakeholders and investing partners throughout research and implementation, to encourage a steady flow of funding and investment. Industry investment could further be reframed as an investment in our future, for the sake of planetary perpetuity.

iii. OTHER INTERVENTION BENEFITS AND INCENTIVES

Seaweed crop cultivation has the potential to affect additional positive climate change benefits, beyond reductions in enteric ruminant methane emissions. For instance, A. taxiformis cultivation at scale could help combat local impacts of *ocean acidification*, which results from oceanic over-absorption of anthropogenic carbon dioxide emissions. The more carbon dioxide absorbed by the ocean, the more acidic the ocean becomes, and the more harmful disruptions to underwater ecosystems. During seaweed cultivation, seaweed absorbs dissolved carbon dioxide and removes it from the ocean, reducing negative impacts for ocean ecosystems (NOAA, 2020). Seaweed also absorbs dissolved phosphorus and nitrogen from point-sources and stormwater runoff, which lead to algal blooms that deplete dissolved oxygen upon decomposition, causing further disruptions to healthy ecosystem function. Seaweed cultivation absorbs dissolved phosphorus and nitrogen, further reducing negative climate change impacts, by aiding in the restoration of dissolved oceanic oxygen (Mernit, 2018). Therefore, assuming some level of macroalgae cultivation in the ocean, scaling up implementation of this intervention would have important environmental health benefits and implications for global climate change,.

iv. POTENTIAL DRAWBACKS AND COUNTERARGUMENTS

Primary drawbacks to proposal implementation at scale include the necessity of additional, in-depth research to address pending questions of intervention efficacy. Further research to answer these and related concerns will be essential to enhancing the long-term sustainability and efficacy of this initiative at scale. For instance, study conclusions point to the need for future research to assess long-term effects of A. taxiformis feed additives on ruminant livestock, in terms of milk composition and quality (Min et al, 2021; Toro-Mujica, 2021). Several studies also recommend further research to assess the long-term effects of A. taxiformis feed additives on ruminant health biomarkers, including fermentation efficiency and rumen fluid metabolic profiles. Similarly, researchers also recommend further R&D in assessing the long-term health impacts of bromoform bioactive compounds on rumen health and digestibility (Min et al, 2021; Toro-Mujica, 2021). Furthermore, study conclusions point to the need for additional small-scale pilot research, to assess rumen effects in in vivo in dairy cattle (Roque et al, 2019). Other studies have further identified the need for future small-scale pilot research in pasture fed cattle consuming roughage diets, as feed additives are likely to induce differing anti-methanogenic effects in pasture-fed ruminants from feedlot cattle (Ridoutt et al, 2022). Insights to prospective solutions would better inform effectual proposal implementation.

IV. POLICY OPTIONS AND RECOMMENDATIONS

i. SHORT-TERM POLICY OPTIONS AND RECOMMENDATIONS

In considering short-term policy opportunities, launching a federal-level consumer marketing campaign in advance of large-scale implementation would help in better understanding nuanced consumer acceptance of macroalgae livestock feed additives and of “low methane beef” prior to market entry. Indeed, it will be difficult for the industry and federal government alike to launch a large-scale seaweed-fed livestock campaign, until such the market already exists in some established capacity. Assessing consumer beliefs of the acceptability of “low-methane beef” alternatives prior to market entry would also serve to identify areas of concern in enhancing consumer and market acceptance in the long-term. Such measures would also enhance cost-effectiveness of initial small-scale investments, and of future large-scale investments in A. taxiformis R&D (Vijn et al, 2020). Relatedly, consumer marketing campaigns could be leveraged to begin mobilizing the public, to demand enhanced government action in addressing climate change, in effect increasing consumer demand for these and other opportunities to begin transition to sustainable economies of scale in the U.S. Also, market incentives could use employed to stimulate interest in the widespread adoption of ruminant feed additives.

Additionally, in the short-term, and before scaling up this intervention nationally, substantial investment will be needed to increase R&D and answer questions of the long-term impacts of A. taxiformis feed additives on ruminant livestock health and fermentation efficiency. Similarly, there are opportunities for collaboration with The *Australian Seaweed Institute Blueprint for Growth* for instance, which specifically touts increased cultivation of

A. taxiformis as a key opportunity for sustainable economic growth. A U.S. federal government partnership with the Australian Seaweed Institute thus has promising potential to enhance data sharing and implementation best-practices, while further expediting U.S. research capacity to achieve enhanced consistency in the quantity of A. taxiformis produced and cultivated at scale (Kelly, 2020).

As such, short-term policy recommendations include: (1) development of targeted, consumer marketing campaigns to enhance intervention success, and to identify optimal strategies of persuasion most likely to enhance the long-term efficacy of intervention implementation at scale, and (2) establishment of U.S. federal government-Australian Seaweed Institute Partnership, to expedite R&D capacity of the U.S. to achieve enhanced consistency in the quantity and quality of A. taxiformis production at scale.

ii. MID-TERM POLICY OPTIONS AND RECOMMENDATIONS

In considering mid-term policy and investment opportunities, it will be imperative to build on findings from expedited R&D as above, to continue answering questions of the long-term impacts of A. taxiformis feed additives on ruminant livestock health and fermentation efficiency. This would aid in better establishing the long-term safety and efficacy of A. taxiformis for use as a ruminant feed additive, which will be imperative in attaining necessary regulatory approvals prior to scaling up this intervention. Investment at this stage will be especially crucial, in terms of overcoming fundamental barriers in optimizing anti-methanogenic properties A. taxiformis production, including maximizing solar energy conversion, and maximizing carbon capture targets for algae fuels (White, 2021). Addressing these barriers early on will enhance resulting enteric methane emissions. To catalyze and incentivize continuous, in-depth A. taxiformis R&D at scale, government subsidies may also be warranted in the mid-term. While it may be impossible to speed up research processes, sufficient R&D funding could mean small and large-scale trials could be run concurrently, leading to quicker solutions to more rapidly inform effectual production. Similarly, it will be imperative in the mid-term to begin recruitment of private wealthy philanthropic investors interested in biofuel production, such as the Gates Foundation, to further enhance sustainability of investments.

As such, mid-term policy recommendations include: (1) catalyzing and incentivizing A. taxiformis R&D at scale with government subsidies, to conduct concurrent small and large-scale trials, leading to quicker solutions to more rapidly inform effectual production, and (2) establishing sustainable financing opportunities, including recruitment of wealthy investors to enhance the potential for long-term intervention success.

iii. LONG-TERM POLICY OPTIONS AND RECOMMENDATIONS

In considering long-term policy opportunities, and assuming short-term and mid-term policy considerations are addressed as above, the next steps involve large-scale industry implementation. By this point, pending concerns of inconsistent production and cultivation quality and quantity would be addressed, and as such, industries would feel confident in projecting biomass yields and respective reductions in enteric methane. To enhance industry compliance upon implementation, it may be helpful to first incrementally introduce and pilot this intervention in smaller-scale feedlot settings (Ridoutt et al, 2022). Once intervention efficacy and safety can be firmly established by the industry in smaller-scale U.S. feedlots, scaling up intervention by larger-scale livestock farmers will be much more feasible. Relevant to this proposal, ruminant feed additives would be subject to federal regulation by the *FDA Center for Veterinary Medicine* (CVM) and “low methane” animal products would be subject to USDA federal regulation. Industries should work in collaboration with CVM and USDA throughout implementation, to ensure complex industry requirements are met by each production site, which in turn would encourage maximized enteric methane reductions at scale. Opportunities to implement enforcement mechanisms on behalf of CVM and USDA should also be explored. As such, long-term policy recommendations include: (1) incrementally introduce and pilot intervention in smaller-scale feedlot settings to sustainably gain wider industry acceptance, and (2) industry collaboration with CVM and USDA throughout implementation processes, to ensure complex industry requirements are met, and to encourage maximized enteric methane reductions at scale.

V. CONCLUSIONS

i. STUDY LIMITATIONS

Methods of data collection among in vivo and in vitro studies reviewed for this report differ. However, study comparisons recapitulate general study findings, and as such, comparisons are acceptable for purposes of this thesis, in exploring the general feasibility of scaling up this intervention to the national level.

ii. ADDRESSING SUSTAINABILITY ISSUES BEYOND THE PILOT PHASE

Beyond the pilot phase, the primary sustainability challenges in scaling up this intervention nationally involve enhancing sustainability in the production, distribution and transportation of the unprocessed A. taxiformis macroalgae and of the processed A. taxiformis feed additive. Specifically, transportation of the A. taxiformis macroalgae and distribution of the A. taxiformis feed additives should be minimized as much as possible

(Roque et al, 2021). Ideally, the macroalgae would be cultivated in close proximity to the feed additive production facilities, as well as to the intended transportation destination, to minimize total distance traveled and enhance sustainability at all levels of implementation.

Unless and until global GHG emissions including methane are substantially reduced, such that rising average global temperatures are capped well below 2°C, deleterious destruction to global ecosystems is an absolute certainty in the coming decades (Wuebbles, 2017). Today's decisions by the international community, especially by major GHG emitters like the U.S., to either act on or ignore the catastrophic reality of the climate crisis, will ultimately determine the magnitude and severity of future climate change impacts. Upon implementation at scale, this intervention presents an important, unique opportunity to speed up the essential adoption of U.S. meat and dairy industry sustainability standards, while rapidly decreasing U.S. methane emissions. As the world's second largest emitter of anthropogenic methane, the U.S. must accept accountability for a proportional reduction of anthropogenic GHGs including methane, or else fate the international community to inevitable climate catastrophe.

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