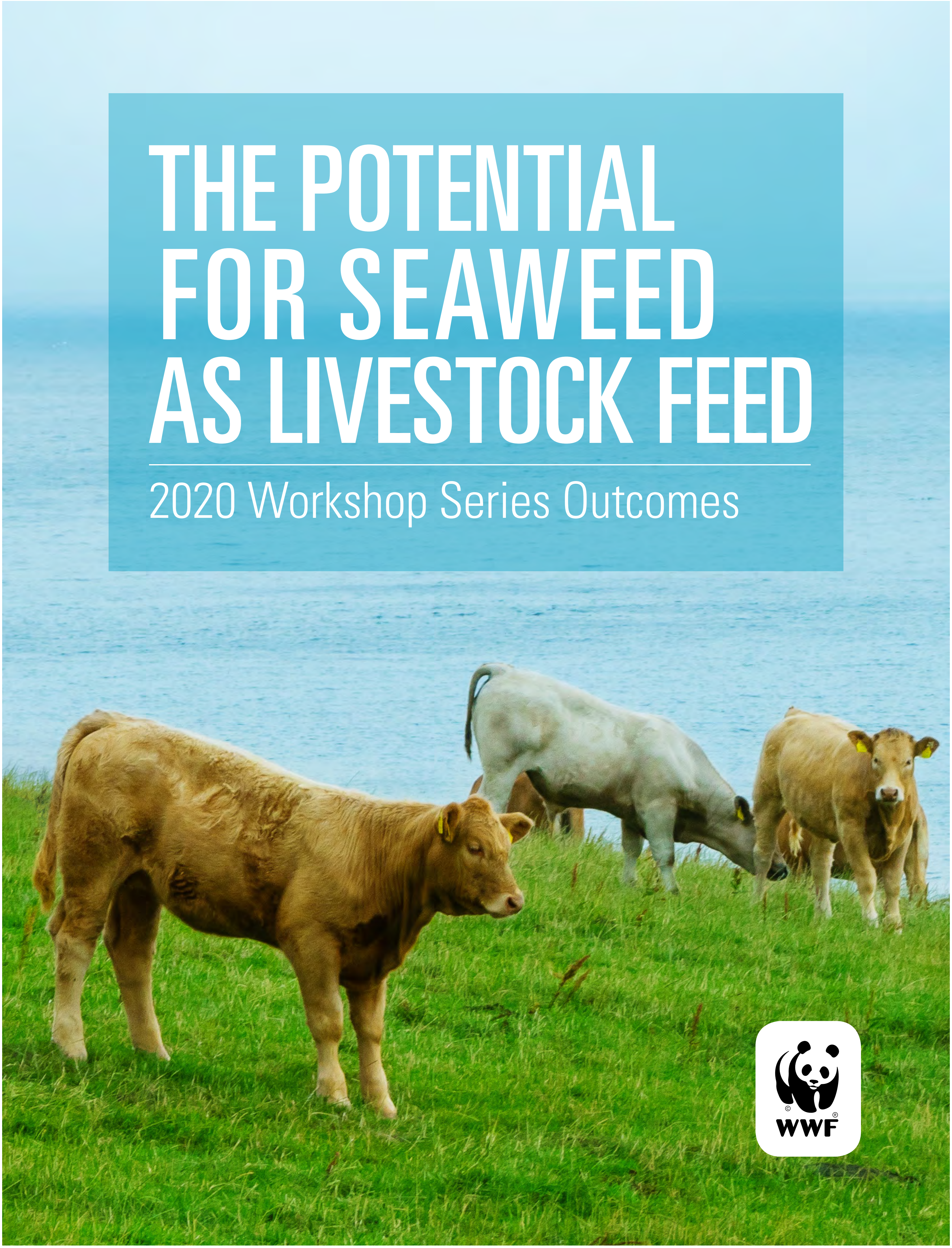
THE POTENTIAL FOR SEAWEED AS LIVESTOCK FEED

2020 Workshop Series Outcomes



The Potential for Seaweed as Livestock Feed

2020 Workshop Series Outcomes

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2020 Workshop Series Outcomes

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and the Foundation for Food and Agriculture Research.
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TABLE OF CONTENTS

Executive Summary 1

Introduction 4

Workshop Design and Objectives 5

A Global View of Research and Development 6

Pre-Workshop Breakout Sessions 9

Productivity and Health Outcomes for Seaweed-Fed Livestock 9

Evaluating the Composition of Seaweed for Potential Use in Feeds 12

Validating Greenhouse Gas Measurements 19

Main Workshop 24

The Pathway Ahead for Seaweed as Livestock Feed 24

Suggested Next Steps And Concluding Remarks 32

Appendix A: 2020 Workshop Series Attendees 34

Appendix B: Directory of Research Projects 39

Appendix C: Breakout Session and Main Workshop Agendas 47

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EXECUTIVE SUMMARY

There is growing global interest in the potential for seaweed to reduce enteric methane emissions from ruminants and improve animal health and productivity when included as a component of livestock feed. In fall 2020, World Wildlife Fund (WWF)—in coordination with the Advanced Research Projects Agency-Energy (ARPA-E), Bigelow Laboratory for Ocean Sciences, and the Foundation for Food and Agriculture Research (FFAR)—convened a multi-part virtual workshop on this emerging topic with more than 130 international stakeholders.

The workshop brought together researchers, industry, non-governmental organizations and other interested parties to identify research needs and discuss the opportunities and challenges of integrating and then scaling up the use of seaweed as a widely consumed livestock feed product. Facilitated as a series of events, the workshop consisted of three distinct breakout sessions followed by a main event.

The conveners designed the workshop series (breakout sessions plus main event) as a forum to help guide the evaluation of seaweed as a safe and effective livestock feed ingredient, compile a directory of emerging research from around the globe, and begin mapping out a collaborative pathway ahead that identifies and fosters opportunities for regional and international coordination.

Pre-workshop online surveys helped prioritize topics of interest and gather information for the research directory. Collaborative engagement among workshop participants started with three virtual breakout sessions, each focused on a distinct topic:

- Productivity and health outcomes for seaweed-fed livestock.
- Evaluating the composition of seaweed for potential use in feeds.
- Validating greenhouse gas measurements (GHGs).

In each session, a panel of experts helped frame group discussion around the primary topic. Participants focused on research needs, data gaps, and key considerations for the work ahead. Outputs from all three breakouts were then shared and built upon at the main workshop. At this larger event, participants again utilized breakout groups, followed by full group discussion, to explore research questions, needs, and priorities linked to one of two scenarios:

- Seaweed products for animal feed.
- Seaweed supplements for enteric methane suppression.

Across the workshop series, participants identified, discussed, and focused in on a wide range of topics that no doubt will require greater attention moving forward. The main event, attended by more than 100 people, brought together participants from each breakout session, as well as other interested parties. Primary topics considered, listed in no order of importance, included the following:

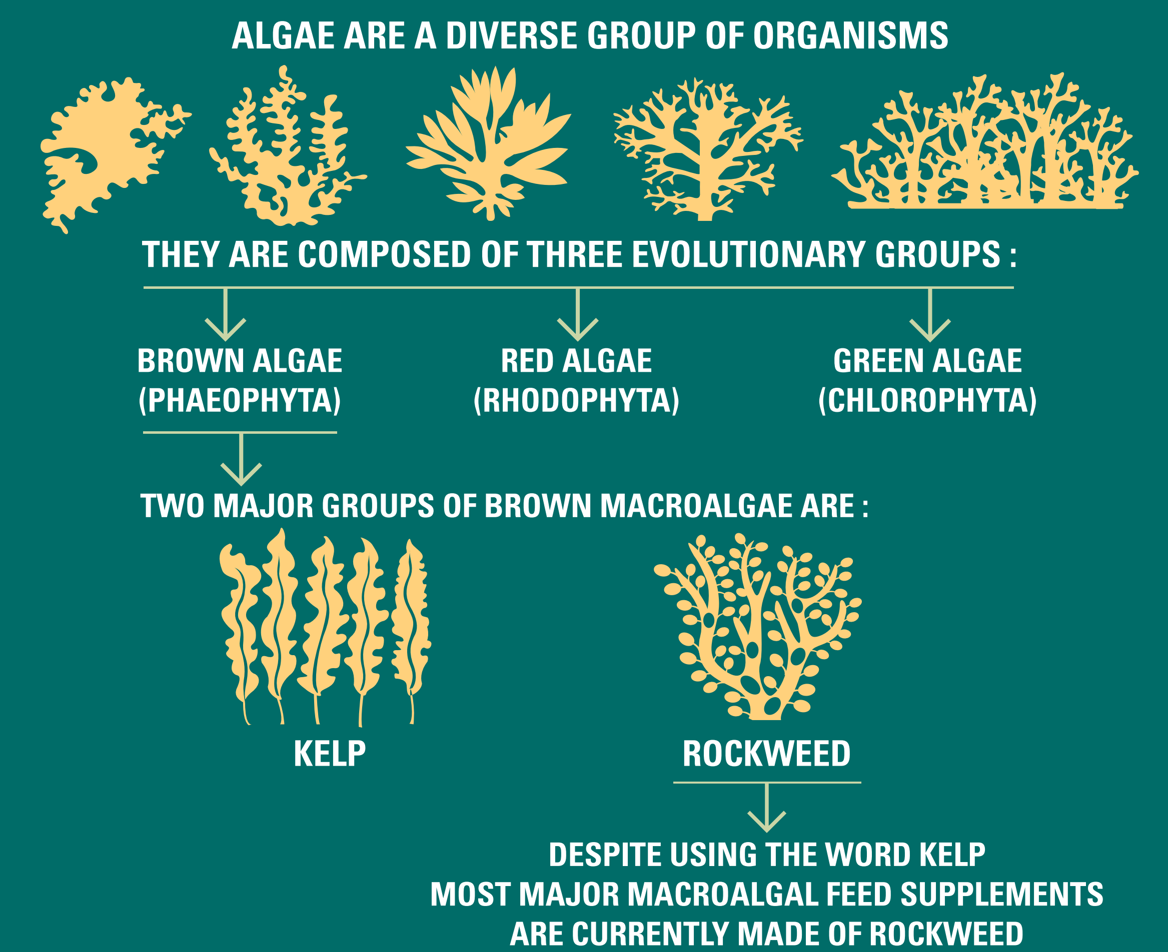
- Variability of seaweed composition.
- Cost-effectiveness of seaweed products.
- Composition of seaweed for animal health.

- Processing methodology.
- Scalability.
- Life cycle analyses.
- Transportation/supply chain.
- Dose and palatability.
- Manure management implications.
- Regulations.

This summary report describes key findings and major takeaways from the 2020 workshop series. Suggested next steps will help guide researchers, funders, and policy makers—and shape the intersection that brings their respective work together—as the parties advance our collective understanding of seaweed as a potentially suitable livestock feed ingredient. The directory of relevant research projects taking place at the time of the main workshop is included below (Appendix B). Likely to expand over time, the directory is expected to foster communication, information sharing, and collaboration, and thereby reduce redundancy in research.

The workshop conveners hope the information exchanged among participating parties, knowledge gained, and connections made during the workshop series will in time make a significant contribution to validating seaweed as a suitable feed ingredient for livestock. It is broadly understood that much work lies ahead on this important issue.

Box 1. Algal Feed Identification

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INTRODUCTION

Enteric methane emissions from ruminant animals raised for meat and milk are a significant contributor across the globe to anthropogenic climate change. Early studies suggest seaweeds offer a promising, natural approach to enteric methane mitigation. In terms of suitability for animal consumption, numerous anecdotal observations exist from different parts of the world of cows and sheep grazing on seaweed along the shoreline. However, to date limited science has emerged that conclusively demonstrates the effect of seaweed as feed, or as a feed ingredient, on animal health and well-being.

For beef and dairy farmers, it is critically important to maintain or improve animal health, performance and productivity. While feeding seaweed to cows and other ruminants may help curb methane outputs, no farmer will use seaweed as a feed ingredient if the product adversely impacts animals. As a developing area of science, many questions must be asked and answered before it is determined that seaweed-based ingredients are effective, safe, profitable, and sustainable along every step of the value chain, from ocean to farm to human consumption.

Promising new developments, combined with broad interest in this emerging area of science, prompted the need for in-depth discussions into the potential for seaweed supplements to both mitigate enteric methane and improve livestock production. Moreover, an important paper has emerged, *Key Considerations for the Use of Seaweed to Reduce Enteric Methane Emissions From Cattle*, which takes a comprehensive look at the issue and will be a key benchmark for work ahead.


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WORKSHOP DESIGN AND OBJECTIVES

The workshop conveners designed and facilitated this series of events to enable exploration of priority topics of interest among participants, advance development of a research directory, and begin to foster coordination and information exchange in order to improve the consistency of research globally and across different types of seaweed species and ruminant herds.

The workshop consisted of three distinct breakout sessions (October 20-22), followed by a main event (November 12). Due to the COVID-19 pandemic, each event took place in a virtual format, rather than a face-to-face setting. One upshot, however, is that this online platform enabled live communication, information sharing, and collaboration among more than 130 stakeholders from 23 countries, making this truly a global event (Appendix A).

A pre-workshop survey revealed priority topics of interest among those expected to participate. Survey results informed selection of the three breakout topics, and helped set the agenda for each session. All three events were structured similarly. Each included expert presentations, designed to frame up the session topic, followed by interactive discussion among all participants. The three breakout session topics included:

- Productivity and health outcomes for seaweed-fed livestock.
- Evaluating the composition of seaweed for potential use in feeds.
- Validating greenhouse gas measurements.

The collective breakout session outputs set the stage for the main workshop. This larger event enabled further exploration of key research questions and associated next steps, and then focused discussion on how coordination should occur under two distinct scenarios: 1) seaweed products for animal feed, and 2) seaweed supplements for enteric methane suppression.

Building on the breakout sessions, the main workshop positioned participants to:

- Identify and consider the necessary conditions for successful incorporation of seaweed into animal feed.
- Inform the pathway forward to guide research and development of seaweed as potential livestock feed that reduces enteric methane emissions.
- Identify next steps to develop a common research framework—consistency of research across continents, across different seaweed species, across types of ruminant herds, and extensions of such methods to other animal species.
- Begin developing strategies for effective coordination among all stakeholders.

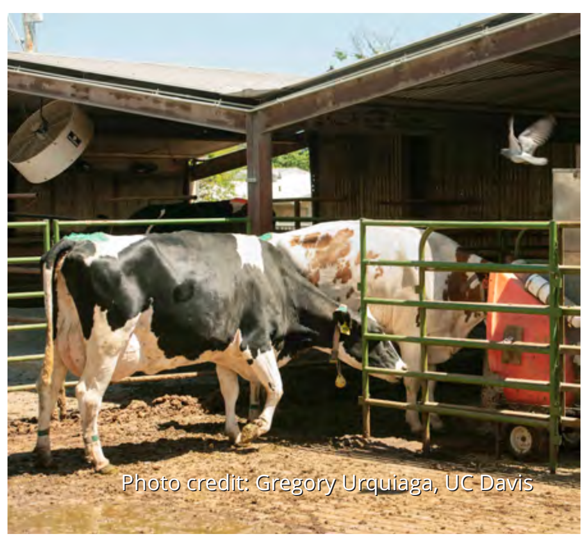


Photo credit: Gregory Urquiaga, UC Davis

A GLOBAL VIEW OF RESEARCH AND DEVELOPMENT

To foster improved understanding of current and emerging seaweed research around the globe, stakeholders were invited to complete a second survey in advance of the main workshop and share high-level details of their respective projects. A total of 32 organizations working on 39 different projects responded to the survey. Information collected is expected to help interested parties identify research gaps, minimize redundancy, and highlight potential areas for future collaboration.

Figure 1 and the associated tables below summarize initial survey responses received to-date. Organizations, agencies, and institutions currently engaged in seaweed feed research who have not replied to the survey are encouraged to contact the WWF aquaculture team and do so. Appendix B includes the full directory of identified research projects.

Figure 1. Funding sources for seaweed projects around the globe. (Some projects have more than one funding source. Percentages may total more than 100%.)

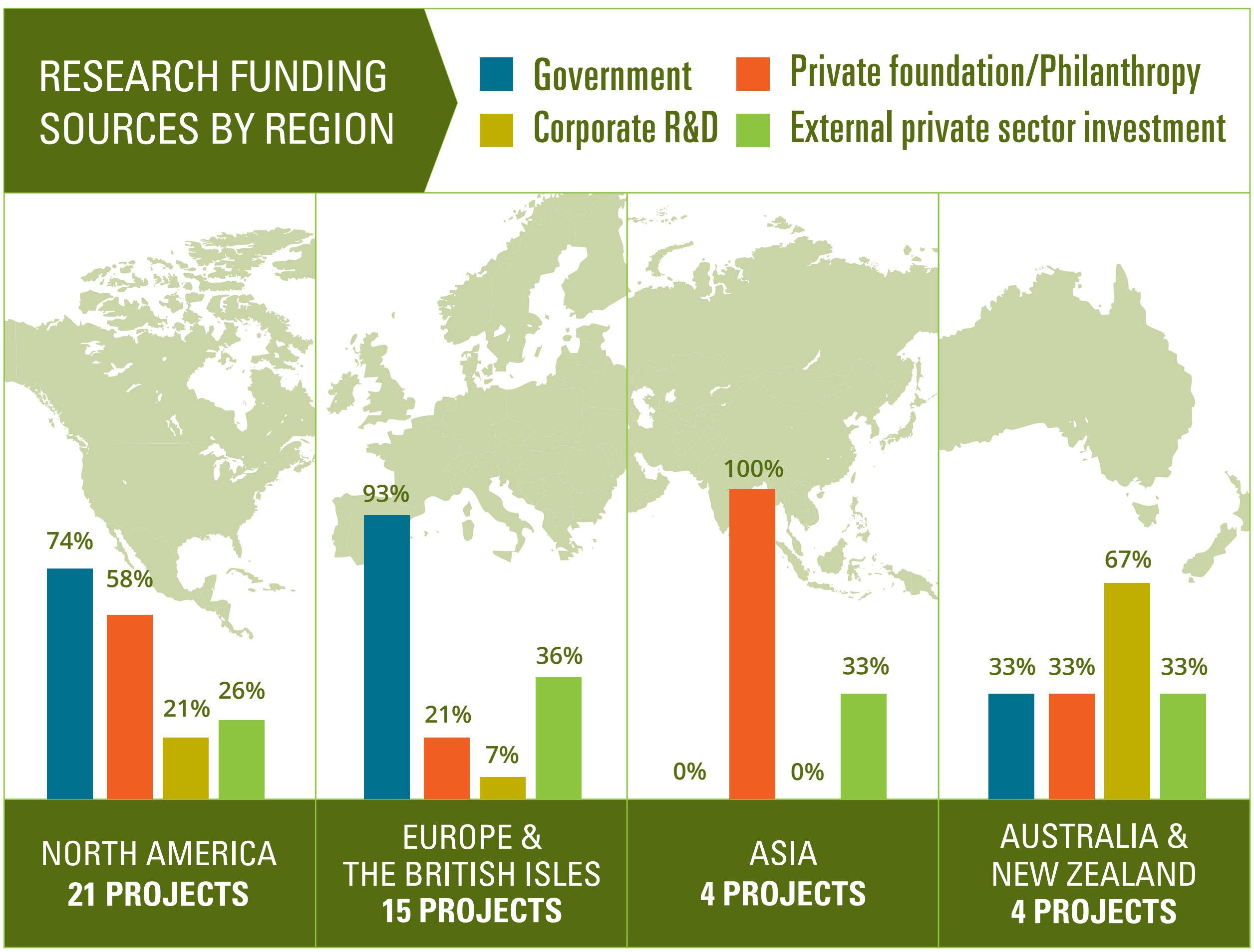


Table 1. Seaweed projects around the globe.

ANIMAL HEALTH & PRODUCTIVITY	Project Numbers
Growth Traits (e.g., average daily grain, feed conversion efficiency)	16
Production Traits (e.g., milk volume/quality and meat quality)	14
Reproductive Success (e.g., conceptions/ live births)	2
Mastitis	2
Respiratory Diseases	1
Metabolic Diseases (e.g., heat stress, liver abscesses, lameness)	2
SEAWEED ANALYTICS	**Project Numbers**
Bioactive Compounds to Disrupt Enteric Methane	23
Health (e.g., minerals, trace elements, antioxidants, fatty acid profiles, amino acids)	19
Base Diet (e.g., dry matter, protein, fiber, starch, fat, ash, lignin)	16
Safety (e.g., heavy metals, pathogens, contaminants, norovirus)	11
GREENHOUSE GAS EMISSIONS	**Project Numbers**
Respiration Chamber	11
Sulfur Hexafluoride (SF6) Tracer Method	2
GreenFeed System	11


Photo credit: Wando County, Korea


Photo credit: Ocean Rainforest

PRE-WORKSHOP BREAKOUT SESSIONS

Productivity and Health Outcomes for Seaweed-Fed Livestock

Session rationale: The 2019 workshop identified a need for both short and long-term trials to confirm that seaweed-based feed ingredients indeed do mitigate methane, while causing no negative impacts to the animal. Ideally, some seaweed feed ingredients will have beneficial effects on animal productivity and health. However, unless and until that performance gain is enough to offset the cost of the product, it may not yet make economic sense for beef and dairy producers to use seaweed.

Session goal: Begin to prioritize research questions needed to assess the impacts of seaweed-based feed ingredients on performance, health, and productivity of meat and milk producing animals.

Expert Panel Presentations

Productivity and Health Outcomes for Seaweed-Fed Livestock
Matthias Hess, PhD., University of California, Davis

Dr. Hess reviewed the high degree of complexity between intestinal microbiomes and feed systems, and the challenges to evaluating the value of different seaweed species as feed ingredients. The composition of an animal's microbiome directly impacts methane output. New molecular approaches now enable researchers to obtain a mechanistic understanding of the molecular processes within and between microbiomes and feed systems. This new knowledge will enable identification of microbial genes and proteins that can be targeted for advanced methane mitigation strategies that also promote animal health and productivity.

Regulatory Considerations for Feed Additives
Juan Tricarico, PhD., Innovation Center for US Dairy

In the United States, the Food and Drug Administration (FDA) is the primary federal agency tasked with regulating animal feed and pet food. However, most regulations that animal feed/food manufacturers must meet are state feed laws. Dr. Tricarico highlighted two primary regulatory considerations for feed additive approval: safety and efficacy. Safety: ensuring the feed additive is safe for both farm animal consumption and human consumption of the animal-derived food products under the conditions of intended use; and efficacy: ensuring the feed additive accomplishes its intended use under the conditions of use. Feed additive manufacturers must demonstrate that products meet both safety and efficacy standards.

Box 2. Iodine

All seaweed species are not equal in iodine content, which can also vary within a species geographically, seasonally, and across life stages. High amounts of iodine in feed could have negative effects on both animal and human consumers, particularly if elevated levels are found in milk or meat products. Alternatively, for populations deficient in iodine, controlled supplementation can act to meet dietary needs.

Fortunately, techniques for low-cost, selective iodine reduction or optimization during seaweed processing hold promise, making this a manageable issue. Maximum iodine content must be reported as a percentage on seaweed feed labels in Canada and is likely important to any regulatory body around the globe. Measuring iodine content is therefore critical.

Interactive Group Discussion

Following panelist presentations, session attendees participated in an informal polling exercise based on the following question:

> *In your opinion—assuming that the candidate seaweed meets safety and efficacy standards—how important is it to assess if [animal outcome] could be impacted by using seaweed as a feed ingredient?*

Animal outcomes polled (i.e., inserted into the question):

- Production traits.
- Growth traits.
- Reproductive success.
- Effect on the calf (nursing or *in utero*).
- Mastitis.
- Identification of bioactive compounds.
- Respiratory diseases.
- Metabolic diseases.

Key exercise take-aways:

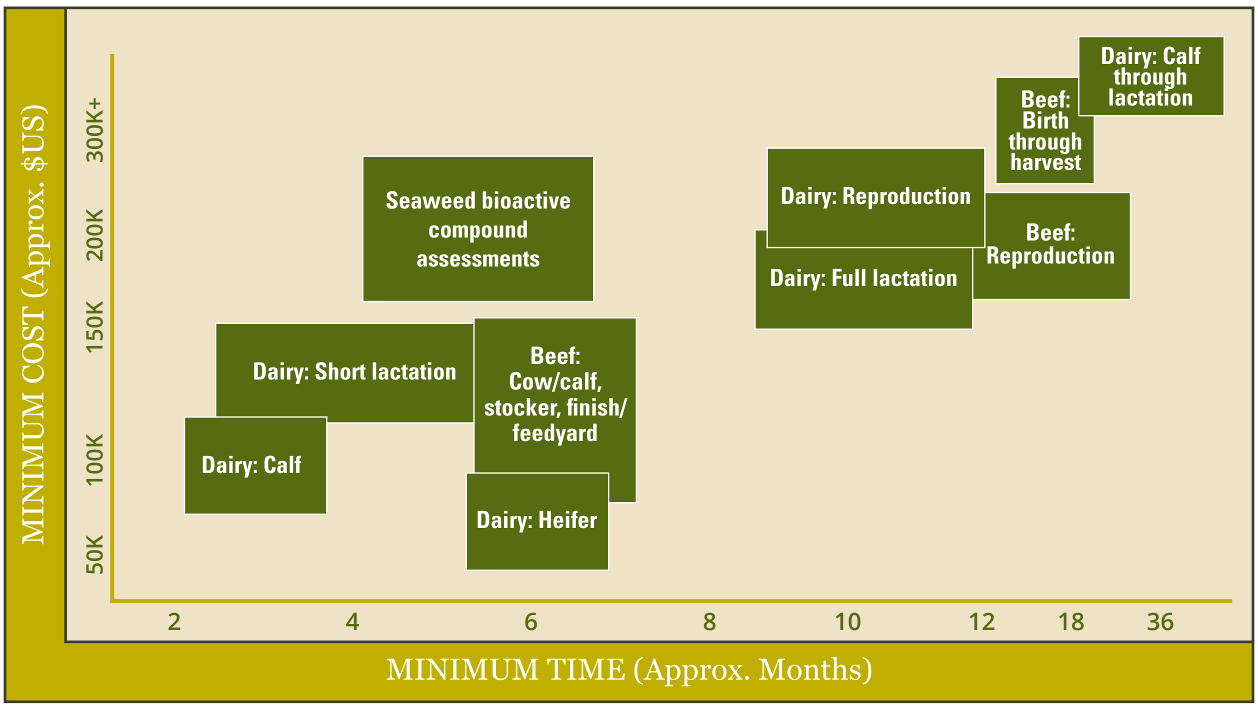
- Effects on reproductive success were considered less critical to assess than production and growth traits. This is likely because any feed ingredient must have a neutral or positive impact on production, or it will not be selected for use by the farmer. Reproductive impacts may also be more difficult and time-intensive to measure and are therefore a lower immediate priority.
- Some potential impacts can be evaluated using fewer animals, but for diseases, mastitis, and reproduction, evaluation will require thousands of animals on commercial farms.
- The ability to positively influence production traits will likely equate to improvements in animal health and efficiency.
- Examination of bioactive compounds may be of higher importance to seaweed producers, to better inform their cultivation efforts.
- Regulatory requirements should largely guide which animal responses to evaluate. Requirements may vary by country.

During this session participants also began construction of a simple diagram to visually demonstrate approximations of cost and time for conducting certain studies. As with the straw poll exercise, figure 2 below represents a starting point for greater consideration.

The boxes indicate range approximations. Presented ranges and numbers are derived from an example experience of a hypothetical large feed company with the benefit of economies of scale and ample labor and equipment to conduct studies. Additional considerations:

- Projected cost estimates are for one study only.
- Costs are not inclusive of potential overhead charged by universities and institutions.
- Three or more additional months are needed for sample analysis and statistics.
- Additional costs for methane analysis (e.g., SF6 tracer) could add $25,000-$75,000.

Figure 2. Minimum time and cost estimates to conduct different types of studies that assess the impact of feeding livestock seaweed.



The following considerations were put forward during discussion of figure 2 above:

- Cost is often associated with the number of animals needed for a study. This is commonly determined by efficacy of the feed ingredient itself. The greater the effect, the fewer animals required for a study to have sufficient statistical power.
- If studying impacts on calves *in utero* or pre-weaning calves, the study may be longer term and need to continue until the calf has entered the milking herd. Rumen undergoes significant change during this period of life and could offer an opportunity to manipulate calf microbiota and reduce methane emissions.
    - It is more challenging to supply a calf with a feed additive or supplement than a mature cow. However, if long-term effects are seen, this may present an approach to reducing methane in animals on pasture or range.

- Lactating research should consider targeting methane emissions in lactating dairy cows, as these cows consume the most and therefore produce the most enteric methane.
- Metagenomics and bioactive compound assessments may be accomplished on a short time scale but can be very expensive.
- Reproductive studies potentially take many years.
- This time versus cost graph is for a single study. Production of a robust estimate of mitigation or production impacts would require several studies with various animals in different locations and/or using different management strategies.

Evaluating the Composition of Seaweed for Potential Use in Feeds

Session rationale: Substantial variability exists between and within seaweed species in nutritional profiles and bioactives, such as bromoform, that reduce enteric methane. Possible factors responsible for this variability may include seaweed species, genotypic diversity, season, life stage, and processing methods. Researchers and feed manufacturers must determine how to prioritize which compounds to test, optimal testing methodologies, and how to produce sufficient seaweed biomass of consistent quality for integration into the supply chain.

Session goals:

- Identify important compounds to test when using seaweed as a supplement or feed constituent for livestock.
- Discuss best practices for consistent, comparative evaluation of active compound levels, enzyme activity, potential contaminants, and nutritional profiles in seaweed products using standard protocols.

Expert Panel Presentations

Challenges and Opportunities in Research and Design

Yan Sun, PhD., Cargill

Dr. Sun acknowledged the difficulty in determining where to begin with research. Many issues must be considered while developing seaweed products for livestock application. For example, it is essential to consider safety of the ingredient (e.g, processing, handling, animal, consumer), effectiveness, environmental impact, stability, quality, waste, current market for the product, and potential return on investment for both farmers and industries. She emphasized the value of cooperation between seaweed and feed industries during early stages of any research effort. Dr. Sun recommends research focus and trial design based upon the needs of the farmers and mode of action of seaweed products.

Safety of Seaweed as Livestock Feed: Key Monitoring Indicators and Challenges

Lalitha Gottumukkala, PhD., Celignis Analytical

Seaweed is one of the most complicated biomasses to analyze and each seaweed type requires extensive method development to extract and analyze the compounds of interest. Seaweed is rich in nutrients but can also have toxins above permissible limits due to their nature of accumulating organic and inorganic compounds present in their environment.

Dr. Gottumukkala discussed opportunities for reducing the risk of contaminants in seaweed during cultivation, harvest, and processing. She recommends establishment of standard guidelines on the source of the feedstock and standard analysis protocols and international limits for identification and quantification of contaminants in the seaweed-based livestock feed, as well as standardization of labels for products containing seaweed.

A Case Study for Methane Suppression

Stephen Archer, PhD., Bigelow Laboratory

Dr. Archer presented a case study of methane suppression potential in ruminants via seaweed feed, using *in vitro* systems and *in vivo* approaches. Two bioactive compound families—halogenated compounds and phlorotannins—are considered in a study, not only for their ability to inhibit methane production, but also for safety and efficacy concerns, including atmospheric (ozone) impacts. Dr. Archer presented species other than the commonly researched *Asparagopsis taxiformis* that have demonstrated enteric methane suppression potential in benchtop trials. He also discussed how environmental factors influence large interspecific variability in bioactive seaweed content (e.g., seasonal variations in phlorotannin content among seaweed species in Ireland).

Box 3. Halogenated Compounds

Bromoform is the primary halogenated compound found in many seaweeds and is responsible for most of the methane reduction potential reported to date. For this reason, as much bromoform as possible should be retained in the seaweed product. How much is retained versus released will mostly depend on the method chosen for processing. When released, volatile halogenated compounds undergo complex reactions that may reduce ozone in the atmosphere. Some have concern that potentially negative ozone impacts, though regional, could make approval of seaweed feed additives difficult. New United Nations Food and Agriculture Organization (FAO) guidelines for impact of feed on emissions considers the impact of halogenated compounds on ozone. In high enough concentrations, bromoform can also be harmful to animal and human health. These potentially deleterious properties will need to be carefully assessed and managed to maximize methane mitigation benefits and minimize environmental and safety risks in the process of upscaling seaweed feed additive production and its application.


Photo credit Wando County, Korea


Photo credit: Gregory Urquiaga, UC Davis

Interactive Group Discussion

Following panelist presentations, session attendees participated in an informal polling exercise. Attendees were asked:

> *Consider the importance of various target analytes, under two scenarios (thresholds given are arbitrary):*
>
> - *Seaweed as a Supplement (<1% of feed formulation)*
> - *Seaweed as a Feed Constituent (>1% of feed formulation)*
>
> *Apply basic criteria to assess how important it is to measure a particular analyte, ranging from "critical to measure" to "not important/uncertain".*

Table 2 below shows various target analytes considered under the categories of bioactive compounds, health, base diet, and safety. This list was intentionally presented in a high level context, as the number of potential analytes in seaweed matter is in the hundreds. The 1% inclusion rate was chosen subjectively in order to easily differentiate between a supplement and constituent.

If more than 80% of polling responses fell into "critical" or "very important" categories, the analyte is listed in the table as *critical* to measure, following a Pareto type analysis for prioritization. It is listed as *nice to have* if polling results also placed the target analyte in that respective classification. Analytes listed as *uncertain/inconsistent* had an almost even distribution across poll responses.

Table 2. The importance of measuring select target analytes under two scenarios:

- Seaweed as a Supplement (<1% of feed formulation)
- Seaweed as a Feed Constituent (>1% of feed formulation)

Category	Compound	Supplement <1%	Feed Constituent >1%
Bioactive Compounds	Bromoform	++	++
	Phlorotannins		++
Health	Minerals & Trace Elements	++	+++
	Antioxidants	++	++
	Fatty Acids	++	+++
	Amino Acids		+++
Base Diet	Dry Matter & Moisture		+++
	Protein		+++
	Carbs: Fiber (NDF & ADF)		+++
	Carbs: Starch	+	+++
	Fats	+	+++
	Ash		+++
	Lignin	+	+
	Lignocellulosic Sugars	+	+
Safety	Heavy Metals	+++	+++
	Pathogens		+++
	Contaminants	+	+++
	Marine Biotoxins	+	+++
	Norovirus		+

+++ CRITICAL ++ NICE TO HAVE + UNCERTAIN/INCONSISTENT

Key exercise take-aways:

- If seaweed is used in higher volumes as a feed constituent, it becomes increasingly more important to test for a wider selection of the various compounds.
- Health and diet analytes are not as important to assess when using seaweed as a constituent versus a feed supplement.
- Amino acids, fatty acids, minerals, vitamins etc. are essential to measure not only for health effects, but also for potential to optimize animal performance.
- Scattered results for safety analytes could reflect a lack of available information and indicate areas of needed research into cultivation, processing, and storage impacts.

- Linking efficacy to chemical content is critical to any type of meta-analysis.
- Opportunities exist for selectively breeding seaweed. In ongoing seaweed husbandry work, where genotypic 'siblings' are grown side by side, huge variation is seen in chemical composition.
- Product safety regulation, in part, determines the targeted analytes.
- It is critical to confirm that any supplement or constituent has no negative impact on animals; the effects must be neutral or positive.

Box 4. How to Approach Seaweed Analyses

Conducting seaweed analytics is a challenge due to the cell wall structure of algae. Given the relative newness of the market for seaweed in some regions, research labs are currently developing technologies and protocols for conducting seaweed analytics. Suggestions for eliciting consistent and reproducible analyses include the following:

- Create lab-to-lab controls:
  - Send “splits” of samples to more than one lab.
  - Send “spiked” controls of known concentrations or certified reference materials.
  - Carefully consider statistical robustness of inter-lab comparisons (e.g., sufficient replication and sample volume).
- Ask questions:
  - Does the lab regularly work with seaweeds?
  - What are the lab protocols, specifically for extraction from algae?
  - What is the lab accuracy, precision, reproducibility of data?
  - How much biomass is needed, and how is it best preserved for these specific analytics?
- Establish standard approaches for extraction and analysis (e.g., Association of Official Analytical Chemists methods).
- Be ready for seasonal, life stage, and species-to-species variance.
- Consider searching for labs that advertise specific experience with algae.
- Ensure processors adhere to Hazard Analysis Critical Control Point (HACCP) plans.


Photo credit: Wando County, Korea


Photo credit: Kevin Posman, Bigelow Laboratory
DELL

Validating Greenhouse Gas Measurements

Session rationale: Enteric methane is the largest anthropogenic source of methane in the US and globally. Accurately measuring GHGs is critical for entering carbon markets, making progress towards science-based targets, ensuring public trust, and for regulatory approvals. Different methods for measuring emissions may be appropriate under various scenarios. Currently available methods include:

- Respiratory chambers.
- Sulfur hexafluoride (SF6) tracer techniques.
- Portable hoods (e.g., GreenFeed system).
- Modeling.
- Micro-meteorological.
- Laser detection/lidar.

Session goal: Discuss and conduct group learning about various methods available to test enteric methane emissions, and their respective validity and use under different circumstances.

Expert Panel Presentations

Estimating Enteric Methane Production from Cattle

Paul Smith, Teagasc Food Research Centre

Dr. Smith reviewed three methods for estimating enteric methane production, the respiration chamber, SF6 tracer method, and GreenFeed system. All are reliable, but each have pros and cons. The selected method of choice depends largely on the research question. For example, a respiratory chamber is preferable to measure a compound's effect on total (i.e., enteric and hindgut) methane production. The SF6 tracer technique is perhaps better for measuring the effect of different pasture-only diets on methane production. Simultaneously quantifying emissions on a large number of animals is best accomplished using the GreenFeed system.

Environmental Performance of Feed Additives in Livestock Supply Chains: Guidelines for Assessment

Ermias Kebreab, PhD., University of California, Davis

Dr. Kebreab reviewed the United Nations Food and Agriculture Organization (FAO) publication, *Environmental Performance of Feed Additives in Livestock Supply Chains: Guidelines for Assessment*, developed over the last two years. This document provides detailed guidance on how to measure environmental performance in the production of feed additives, and the effects of feed additives on the environmental performance of livestock products. The guidelines apply to various livestock production systems including large and small ruminants, poultry, and pig production systems. Dr. Kebreab emphasized that life cycle analyses (LCAs) must consider upstream and downstream effects of a feed additive and cover the whole production cycle of an animal. In addition, it is essential to model the end-to-end reduction potential of the ingredient, including digestive methane emissions, manure storage, farm management, and crop production.

Carbon Market Mechanisms and Methodologies

Martin Gehrig, PhD., TREES Consulting

Dr. Gehrig provided a high-level review of how carbon credits and supply chain programs can incentivize and support emissions reduction programs from enteric fermentation. He explained that a quantification methodology is a technical document to quantify and monitor GHG benefits for a specific activity. It includes a benefits quantification approach and additional requirements such as applicability conditions, safeguards, additionality, and monitoring criteria. A methodology is required by carbon standards in both the voluntary carbon markets and compliance systems for an activity to generate carbon credits or supply chain emission reductions. The methodology, *"Reducing Methane Emissions from Enteric Fermentation in Dairy Cows through Application of Feed Supplements,"* is registered and ready for application under The Gold Standard.

Box 5. Manure Management

Manure, according to the US Environmental Protection Agency, is the fourth largest source of methane emissions in the United States. Farmers use a variety of on-site manure management techniques. For some this includes anaerobic manure lagoons, which can have high GHG outputs. Anaerobic digesters offer a way to transform or capture methane from manure and offer it as a biofuel for energy production.

Manure composition may change depending on animal diet. It remains an open question as to whether manure from seaweed-fed animals will continue to perform as well in anaerobic digesters. Bioactive compounds from seaweed feed can also accumulate in manure and could lead to changes in soil health where manure is subsequently applied. Impacts on manure management will factor into modeling overall emission reduction potential of seaweed feed and should be incorporated into life-cycle assessments.

Photo credit (left & right): Gregory Urquiaga, UC Davis

Interactive Group Discussion

Following panelist presentations, session attendees were given example scenarios to consider. For each scenario, participants were asked to consider and discuss which method or methods are best suited to quantify emissions. An initial comparative assessment emerged (table 3 below). Many acknowledged this type of comparison warrants further study. Some noted aerial surveillance and laser detection/lidar as emerging methods not listed.

Table 3. Comparison of GHG validation methods.

Method	Number of Animals	Accuracy	Ability to estimate emissions under specific production conditions (e.g., breed, forage, season, etc.)	Cost	Labor	Accepted by Regulators?
Incubation Chamber	+	+++	++	+++	+++	Yes
SF6	+	+++	+++	+++	+++	
GreenFeed	++	+++	+++	++	++	Yes
Modeling	+++++	++	+	+	+	

Key discussion takeaways:

- Accuracy of a method is dependent on the production system, and many other management factors and practices, such as breed, forage, rotational grazing, etc.
- The approaches mentioned above offer the opportunity to estimate in a variety of contexts that could impact accuracy, depending on the objectives of the study. For instance, portable hoods work well in the field but only measure methane when animals are consuming an attractant feed; respiratory chambers require placing animals indoors and providing feed that represents their normal diet; SF6 approaches can measure methane emissions from animals on pasture, whether sitting or standing.
- For seaweed, both production methods (e.g., wild harvest, ocean farming, recirculating aquaculture system) and processing techniques influence emissions factors. Sequestration may make algae production carbon negative.
- Emissions relate to many inputs not yet fully understood (e.g., grass quality, genetics). Having a local measure is key.
- Emissions quantification on a large farm requires baseline measurements. The corporate supply chain cannot easily conduct detailed measurements. Nor can they reliably model emissions because of the many different approaches to handling animals.
- Remote sensing may not presently offer a high degree of accuracy in measurements. Many workshop participants were skeptical that farm-scale measurements can be made, while some advocated for its potential.
- Modeling is currently considered a better route for larger scale quantifications.
- Biological proxies like milk fatty acids and the oral microbiome offer potential for validating methane emissions.
- Modeling can explore the overall reduction potential of not just methane, but also manure storage, farm management, and crop production.
- Some suggest emissions be measured first to ensure the reduction factor is experimentally determined, then model up to a larger scale.
- Frequent calibration of any system is required.


Photo credit: Paul Smith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MAIN WORKSHOP

More than a hundred stakeholders, representing research and production of seaweeds, animal feeds, beef and dairy cattle, and beef and dairy food companies, gathered for the main workshop. Many had previously attended one or more of the pre-workshop breakout sessions, as well as the inaugural event held in 2019. Paul Dobbins of WWF provided opening remarks and spoke about the promise of seaweed. Jack Lewnard, ARPA-E, followed with a framing presentation on the impacts of methane on climate.

Report backs from each breakout session—including exercise outputs, informal polls, and key considerations that emerged during group discussion—were shared and briefly discussed at the outset of the main workshop. Participants then split into four virtual breakout rooms to further discuss and identify priority research needs and associated questions. Results from these discussions are described below.

Addressing Enteric Methane for a Low-Carbon Future

Jack Lewnard, PhD., ARPA-E

Dr. Lewnard provided the opening presentation. Enteric emissions are the number one source of anthropogenic methane emissions in the United States, and manure is the fourth highest source. Methane's GHG warming potential, he noted, is 28-80 times higher than carbon dioxide. Increasing efficiency (increase meat/milk output per unit of methane) and prevention (reducing the CH_4 emissions per cow) are two ways to reduce methane while keeping the food supply intact. A full LCA is the recommended next step to establish the current base case. Evaluation of methane reduction options can then be done with the same LCA framework. The LCA framework can be used to compare options, as well as the baseline “business as usual” case with purchased carbon offsets.

Dr. Lewnard introduced ARPA-E's proposed REMEDY Program—Reducing Emissions of Methane Every Day of the Year—which seeks to fund novel, disruptive, transformative technologies that could: (a) prevent methane emissions from anthropogenic activities; (b) abate methane emissions at the source; and (c) remove methane from the air. He encouraged workshop participants to learn more and possibly gain support from the program.

The Pathway Ahead for Seaweed as Livestock Feed

Building on information exchanged and discussed at the three pre-workshop breakout sessions, participants at the main workshop, as noted above, were randomly assigned into four small groups. Each respective group identified two to four research needs or questions applicable to:

- Seaweed supplements for enteric methane suppression.
- Seaweed products for animal feed.

Groups then considered possible outcomes of each inquiry under two predetermined scenarios:

- Scenario 1: Seaweed supplements/feeds are safe, scalable, improve animal productivity and/or significantly reduce enteric methane emissions.
- Scenario 2: Seaweed supplements/feeds may not be safe or scalable, may harm animal productivity and/or do not reduce enteric methane emissions.

Time permitting, groups suggested next steps and explored how and when to coordinate efforts moving forward. Table 4 below reflects the overall outputs of small group work. There is no priority or logical sequence to the presented information.

Table 4. Priority research needs, potential outcomes, and next steps.

Evaluate intra-species variability of seaweed composition based on seasonality, environmental conditions, and geographic location

Possible Positive Outcomes

- Ability to control for content of important compounds like bromoform in order to create a product with the desired activity and safety.
- Ability to model concentrations of important compounds like bromoform by location so farmers can select farm sites for best product composition.
- Quality controlled, consistent product available to farmers.

Next Steps

- Set up farms in appropriate locations.
- Determine best processing method to retain important compounds.
- Develop supply chain and transportation to inland farms.
- Conduct "round robin" testing to compare results of seaweed compositional analysis between different labs for consistency and reproducibility.

Possible Negative Outcomes

- Ideal environmental conditions are costly and farms are not scalable.
- Distribution to inland farms is too difficult and costly.
- Cannot determine cause or predictable pattern in variability.

Next Steps

- Test new seaweed species.
- Consider if land-based tank culture offers more control over seaweed composition.

Additional Considerations

- Factors impacting composition may include light, wave energy, pH, temperature, and latitude.
- Farmed seaweed may not have the same variability in composition as wild seaweed since it is grown under more controlled conditions and harvested at the same time every year.

- Consistent and reproducible analyses are necessary before variability can be accurately determined. Standardized methods for measuring composition do not yet exist and will be important for making products comparable.

Determine inclusion level of seaweed in livestock feed that is both effective and palatable to the animal

Possible Positive Outcomes

- Product is sufficiently palatable to sustain high intake rates at inclusion levels needed to achieve methane reduction or positive effects on animal health.
- Seaweed replaces another diet component, thereby making the feed more cost effective or energy efficient.

Next Steps

- Lengthen shelf life to ensure the product remains stable, safe, and available until consumed by the animal.
- Determine if the level of methane reduction from seaweed is competitive with other methods for methane mitigation in animal diets.

Possible Negative Outcomes

- Concentration of anti-nutritional components is too high and creates negative impacts on the animal. There is an upper limit on how much can be fed.
- Unable to safely include seaweed in a high enough dose to sufficiently reduce methane emissions.
- Intake goes down due to palatability decline.
- Taste or quality of the consumer products goes down (e.g., milk and meat).

Next Steps

- Try to remove or reduce negative components through processing techniques.
- Test different processing techniques that may better retain the target compound.
- See if growing conditions can change the target compound content.
- Move on to other seaweed species using screening mechanism.
- If targeting animal health with seaweed as a feed replacement, consider smaller quantities for specific applications like methane suppression.
- Explore other uses for seaweed on the farm (e.g., bedding, stress reliever).

Additional Considerations

- Inclusion will depend on the species. Higher rates of inclusion up to 20-30% may be possible as a feed replacement; <3% for methane suppression.
- Some species have been shown to negatively impact milk production. Small decreases in intake may improve feed efficiency but larger decreases will always lower productivity and close the door on a product.
- Multiple studies and stakeholder experience have shown palatability does not change.

Explore processing techniques that retain desired compounds and are economically viable

Possible Positive Outcomes

- Chosen method is low energy, low cost, and delivers a product that is transportable to inland farms and easily stored.
- Ability to utilize residues of seaweed from other processing pipelines.
- For methane mitigation, bromoform or other target compounds are retained.

Next Steps

- Investigate and optimize different processing technologies.
- Develop biorefinery approach for different end products.
- Compare different stabilization approaches (e.g., freeze drying, fermenting, ensiling).

Possible Negative Outcomes

- Delivery method to the animal is not compatible with farm activities.
- Too much processing becomes cost prohibitive or energetically inefficient.
- Valuable or target compounds are lost in the process.
- Unacceptable concentration of toxins or anti-nutritional factors.

Next Steps

- Look for simplified processing procedures.
- Compare different processing approaches *in vitro*.

Additional Considerations

- Processing techniques, like drying, may help to eliminate safety issues like norovirus, biotoxins, etc.
- Processing technique will play a large role in how the feed ingredient is transported.

Establish scalability and cost effectiveness of seaweed production to reach farms in required volume

Possible Positive Outcomes

- Multiple seaweed species are readily and reliably available for livestock diet inclusion.
- Selected species contain specific functional constituents that are consistently generated in sufficient concentrations.
- Ability to select/breed for important compounds so less volume is needed for inclusion in the feed.

Next Steps

- Determine relative cost effectiveness to livestock producers.
- Determine willingness to pay for analysis, branding, and outreach.

Possible Negative Outcomes

- Species of most interest cannot be cultivated at scale or have environmental concerns.
- Seaweeds have inconsistent yields, high variation in target compounds, high levels of antinutrients, unacceptable levels of heavy metals, other contaminants, or iodine.
- Escapees of bred/genetically modified seaweeds enter the ocean from coastal culture systems.

Next Steps

- Explore closed cultivation methods, recognizing that these result in higher costs and larger carbon footprints.
- Consider microbial engineering or chemical synthesis to scale up production volume for certain compounds/bioactives.

Additional Considerations

- Local species should be prioritized, as well as species already cultivated at scale.
- Cost-effective transportation from ocean production sites to inland livestock farms may present a challenge.
- Awareness is needed of the carbon footprint and total supply chain LCA when considering production, processing, and distribution of seaweeds.
  Mismatch between seaweed cultivation expenses and feed value could be addressed when regulatory drivers (i.e., methane reduction requirements) force market demand. However, cost effectiveness or appropriate financing is still essential, as a regulatory framework could collapse at any time.
- Incentives are needed via voluntary carbon markets or policy-driven state or federally mandated emissions limits. It is unclear which is more effective at incentivizing broad scale implementation, or if both are necessary. While regulations can limit emissions from farms, mandatory use of a particular product like seaweed is unlikely. Seaweed represents but one substance producers could use to meet regulatory requirements.

Determine desirable composition of seaweed that will benefit animal health and productivity

Possible Positive Outcomes

- Increases in feed efficiency as nutritional value is not lost to methane emissions, while at the same time maintaining productivity, reproduction, growth, and meat quality.

- Mortality is reduced in livestock. This has been seen in piglets fed seaweed.
- Seaweed shows specific advantages over terrestrial feed. This can be linked to specific seaweed constituents.

Next Steps

- Evaluate seaweed as a component of different diet compositions.
- Screen different seaweeds *in vitro* and *in vivo* for beneficial compounds.
- Commercial trials for regulatory approval of the seaweed feed.
- Engage with feed mills to ensure feasibility of incorporation into commercial feeds.

Possible Negative Outcomes

- Any negative impacts observed on animal health or productivity.
- Microbial changes from seaweed negatively impact ruminal and animal health.
- Palatability issues arise and intake decreases.
- Milk or meat quality decreases.

Next Steps

- Run trials with lower dose of seaweed feed component.
- Determine what compounds cause negative impacts and find ways to reduce their content through breeding or processing.

Additional Considerations

- A neutral impact on health and productivity may not be enough to encourage use and could also be considered a negative outcome in this scenario.
- Cost savings for the dairy or beef farmer would greatly increase likelihood of adoption.
- Unknown bioactive compounds may occur in seaweed species that improve animal health and productivity.
- Animal safety will generally carry over to safety and health for human consumers.

Investigate mechanism of action on the rumen microbiome for suppression of methane emissions

Possible Positive Outcomes

- Stable microbiome with reduction in methanogens.
- Obvious shifts in the microbial community can be detected and monitored upon addition of seaweed.

Next Steps

- Metagenomics and functional analysis of high throughput "OMICS" data (i.e. genomics, proteomics, metabolomics, etc.)
- Test if long-term use leads to adaptation of ruminal microbiome.

Possible Negative Outcomes

- Addition of seaweed leads to no beneficial impacts on microbial community.
- Unexplained or unanticipated changes in animal traits or behaviors.
- Animal adapts or acclimates to the bioactive ingredient to neutralize effectiveness.
- Food safety pathogens are impacted in a way that may increase food safety risk.

Next Steps

- Test ruminal retention time and feeding frequency required for seaweed to effectively mitigate enteric methane.

Additional Considerations

- Hydrogen buildup occurs when conversion to methane is suppressed. Hydrogen could be redirected to propionic acid which goes back into energy for the cow. However, this could create pressure buildup in the rumen which can reduce feed intake of cows.

It is increasingly recognized that products which suppress methane emissions from ruminants may grow in importance as regulatory bodies begin pushing for emissions reductions from the agricultural sector. Each small group discussed how approval of a feed product by appropriate regulatory bodies, such as the US FDA, is a critical step for successfully incorporating seaweed as a feed ingredient. Conversations between product developers and regulatory agencies should occur early and often. Moreover, it is important to note that this process may differ greatly between countries or for different export markets. Regulatory pathways may be relatively established for nutritive ingredients if animal health is the intended use. Approval of products that claim methane reduction will likely be more involved.

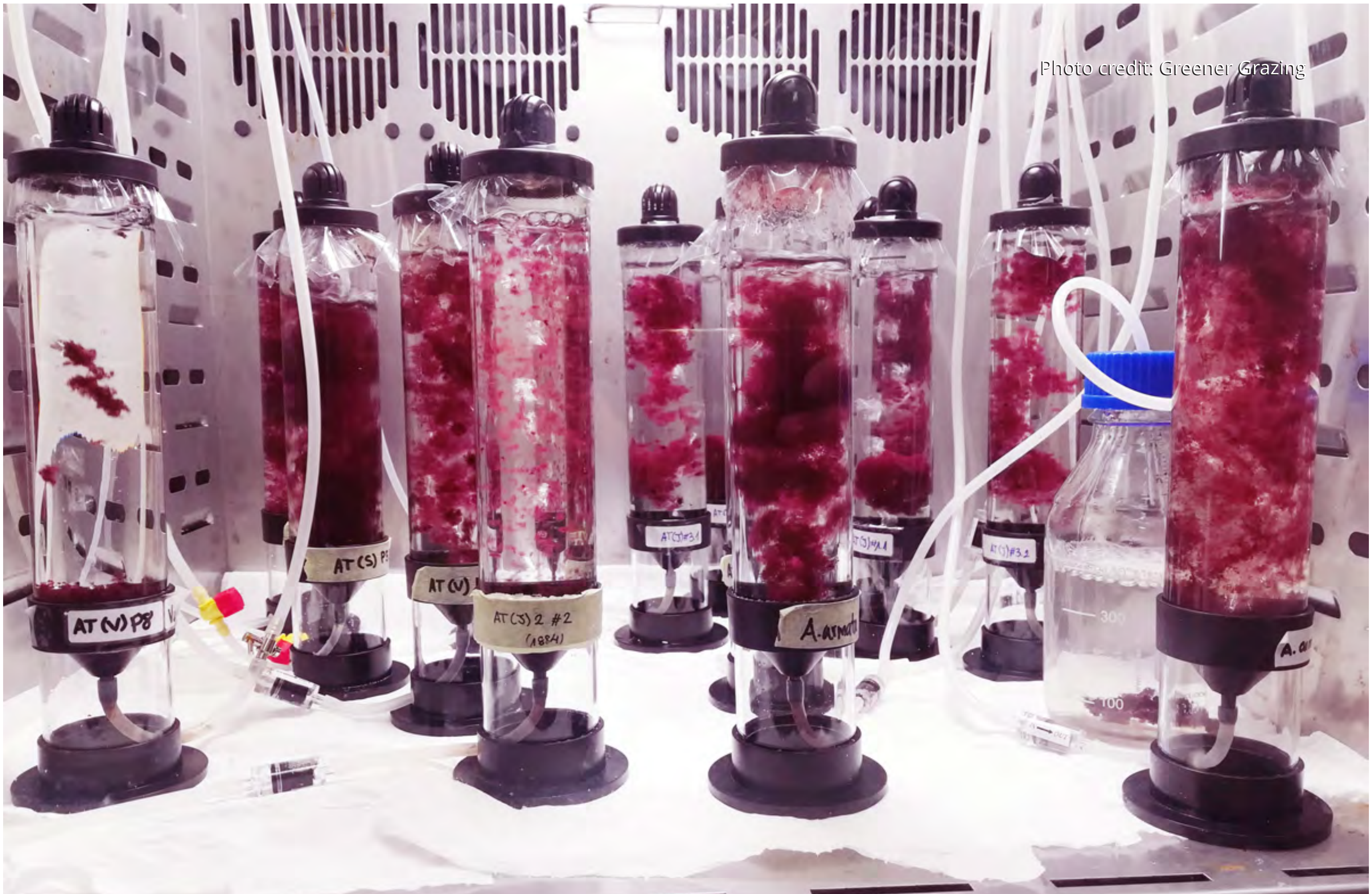

Photo credit: Greener Grazing

Photo credit: Pepe Brix

SUGGESTED NEXT STEPS AND CONCLUDING REMARKS

Combating climate change by exploring ways to reduce causative emissions remains a top priority for policy leaders, industry, scientists, activists, and, increasingly, consumers around the globe. The enthusiastic engagement at this workshop, and broad international participation, suggests coordination on the prospect of seaweed as livestock feed will continue to grow. Participants suggested several tools and coordination strategies moving forward:

- Continue building a directory of research projects, institutions, and labs that can be updated and kept accurate (building on initial survey results).
    - Directory may also include unfunded blue ocean interests, ideas and proposals—particularly those incorporating advanced technology such as drones, machine learning, or other methods to reduce costs of GHG emissions.
- Develop a website repository of related information, research, and news articles.
- Establish a task force, working group, steering committee, or similar body to facilitate international coordination and information sharing.
- Create an email list-serve or *WhatsApp* group to foster regular information exchange.
- Facilitate round-robin research opportunities.
    - *In vitro* methods across continents to compare and demonstrate how different animals, systems and locations react to different seaweeds.
    - Seaweed constituent analytics.
    - Others.

Although this workshop largely focused on the potential for seaweed as a methane mitigant, it is broadly recognized that other potential approaches to mitigate ruminant emissions exist. At the same time, other prospective uses for seaweed in the livestock industry may yet emerge. The speed at which the research community and industry arrive at safe, scalable seaweed feed that improves animal productivity or significantly reduces enteric methane emissions—or simultaneously achieves both of these goals—will largely depend on funding and cross-sector collaboration.

Stakeholders from up and down the value chain gathered to explore and begin mapping out a pathway forward to collaboratively advance research and development of seaweed as a potential methane mitigant. Connections were made across the globe, knowledge and information exchange took place, and ideally, doors opened that will lead to partnerships between individuals and groups working on this important issue. The workshop conveners look forward to continued engagement, both with and between stakeholders who participated, in time leading to a robust body of work that addresses the challenges and opportunities identified during this workshop series.

Photo credit: Greener Grazing

APPENDIX A
2020 Workshop Series Attendees

LAST	FIRST	AFFILIATION
Aasen	Inga Marie	SINTEF
Abbott	Wade	Agriculture and Agri-Food Canada
Akerman	Fredrik	Volta Greentech
Amini	Morteza	California Air Resources Board
Archer	Stephen	Bigelow Laboratory for Ocean Sciences
Ask	Erick	DuPont de Nemours Inc
Augyte	Simona	Ocean Era
Baker	Banks	McDonald's Corporation
Ballard	Katie	The William H. Miner Agricultural Research Institute
Barbosa	Mike	SeaFeed Inc.
Bardies	Gregory	Barry Callebaut
Barney	Brandon	Primary Ocean
Baruch	Seth	Carbonomics
Belle	Sebastian	Maine Aquaculture Association
Ben Aouda	Mohammed	AgroSup Dijon
Beymer-Farris	Betsy	University of Kentucky
Bickford	Julie-Marie	Maine Dairy Industry Association
Boland	Tommy	University College Dublin
Bryant	Peter	Walton Personal Philanthropy Group
Butler	David	Alltech
Calderwood	Louise	American Feed Industry Association
Campbell	Mairead	Queens University
Carvalho	Pedro	University of California Davis
Cayten	Megan Reilly	Oceans 2050
Clark	Jennifer	Cascadia Seaweed Corp.

LAST	FIRST	AFFILIATION
Collins	Bill	Cascadia Seaweed Corp.
Compart	Devan	Land O'Lakes
Coronado James	Marialejandra	NutraSteward
Danaher	Kate	S2G Ventures
Davis	Jed	Agri-Mark/Cabot Creamery Co-operative
Davis	Simon	Seadling
De Camillis	Camillo	Food and Agriculture Organization of the United Nations
Demeter	Angelo	Volta Greentech
Dobbins	Paul	WWF-US
Doraiswamy	Krishna	ARPA-E
Emerson	David	Bigelow Laboratory for Ocean Sciences
Fisher	Jon	The Pew Charitable Trusts
Friend	Emalee	USDA Agricultural Research Service
Garbutt	Pete	McDonald's Corporation
Gehrig	Martin	TREES Consulting
Gottumukkala	Lalitha	Celignis
Grebe	Gretchen	Marine Biological Laboratory
Greenwood	Sabrina	University of Vermont
Gregersen	Olavur	Ocean Rainforest
Grimm	Thomas	Carlsbad Aquafarms, Inc.
Gruninger	Rob	Agriculture and Agri-food Canada
Gunter	Stacey	USDA Agricultural Research Service
Hammer	Betina	Copenhagen University
Hansen	Hanne Helene	University of Copenhagen
Hardie	Adam	Danone North America
Hardman	Tim	WWF-US
Hayes	Daniel	Celignis
Hayes	Maria	Teagasc Food Research Centre
Hayes	Mike	University of Limerick
Hazard	Donna	SeaAhead

LAST	FIRST	AFFILIATION
Helms	Janet	Inter IKEA Group
Hess	Matthias	University of California Davis
Hristov	Alex	Penn State University
Huws	Sharon	Queen's University Belfast
Jansen	Hugo	Cargill
Johnson	Kristen	Washington State University
Johnson	Ron	National Oceanic and Atmospheric Administration
Kalscheur	Ken	USDA Agricultural Research Service, USDFRC
Kebreab	Ermias	University of California Davis
Kim	Jang	Incheon National University
Kraan	Stefan	The Seaweed Company
Kroopf	Sara	McDonald's Corporation
Kurt	Timothy	Foundation for Food and Agriculture Research
Kuwayama	Toshihiro	California Air Resources Board
Laurens	Lieve	National Renewable Energy Laboratory
Lewnard	Jack	ARPA-E
Lindell	Scott	Woods Hole Oceanographic Institution
Lomas	Michael	Bigelow Laboratory for Ocean Sciences
Luhning	Jessica	Organic Valley
Lundgren	Britt	Stonyfield
Marsman	Floor	Ocean Rainforest
Mathiesen	Christoph	IKEA
McBride	Monica	WWF-US
Mettler	Larsen	S2G Ventures
Mitloehner	Qian	California Air Resources Board
Moritz	Bailey	WWF-US
Morrison	Sarah	The William H. Miner Agricultural Research Institute
Muizelaar	Wouter	Wageningen University and Research
Muñoz-Tamayo	Rafael	INRAE
Mydland	Liv Torunn	Norwegian University of Life Sciences

LAST	FIRST	AFFILIATION
Neves	Luiza	Seaweed Energy Solutions
Nielsen	Mette	Aarhus University
Nikel	Kennedy	Cascadia Seaweed
O'Connor	Ryan	University of Southern California
Padam	Birdie Scott	Seadling Pte. Ltd
Parkhurst	Robert	Sierra View Consulting
Powers	Susan	Clarkson University
Price	Nichole	Bigelow Laboratory For Ocean Sciences
Puro	Leah	Wolfe's Neck
Radakovits	Randor	Synthetic Genomics Inc.
Rakobitsch	Nicole	Organic Valley
Ramin	Mohammad	Swedish University of Agricultural Sciences
Ricart	Aurora M	Bigelow Laboratory for Ocean Sciences
Rogers	Shane	Clarkson University
Rubino	Michele	Synthetic Genomics
Salwen	Joan	Blue Ocean Barns
San Pietro	Richard	Synthetic Genomics Inc.
Serin	Spencer	Cascadia Seaweed
Sims	Neil	Ocean Era, Inc.
Singh	Sachi	Interested party
Skinner	Taryn	WWF-US
Smith	Jennifer	Scripps Institution of Oceanography
Smith	Paul	Teagasc Food Research Centre
Sun	Yan	Cargill Animal Nutrition & Health
Talyan	Vikash	Gold Standard Foundation
Tayyab	Usama	Otter Coop
Theodoridou	Katerina	Queens University Belfast
Theurer	Miles	Veterinary Research and Consulting Services, LLC
Tingley	Jeff	University Of Lethbridge
Tricarico	Juan	Dairy Management Inc.

LAST	FIRST	AFFILIATION
van Heugten	Eric	North Carolina State University
Vijn	Sandra	WWF-US
von Keitz	Marc	ARPA-E
von Leesen	Justus	Evonik Operations GmbH
Vrancken	Hilde	The Seaweed Company
Wachowicz	Kelly	Catch Together
Waters	Tiffany	The Nature Conservancy
Weisbjerg	Martin	Aarhus University
Weller	Dan	California Air Resources Board
Williamson	Mike	Cascadia Seaweed
Wilson	Agustin Arturo	WWF-Ecuador
Word	Alyssa	Cactus Feeders
Yarish	Charles	University of Connecticut
Yun	Jin-Ho	Bigelow Laboratory for Ocean Sciences

APPENDIX B
Directory of Research Projects

The current directory is reflective of the participants at the workshop and is intended as a living document. Information is up to date as of November 25, 2020. If interested in having your research included, please contact bailey.moritz@wwfus.org as the workshop Planning Team works to further build out and find a permanent home for this directory.

Overview

Research into Animal Health and Productivity

- 16 Projects: Growth traits (i.e., average daily gain, feed conversion efficiency).
- 14 Projects: Production traits (e.g., milk volume/quality and meat quality).
- 2 Projects: Reproductive success (e.g., conceptions/live births).
- 2 Projects: Mastitis.
- 1 Project: Respiratory diseases.
- 2 Projects: Metabolic Diseases (e.g., heat stress, liver abscesses, lameness).

Research into Seaweed Analytics

- 23 Projects: Bioactive compounds to disrupt enteric methane.
- 19 Projects: Health (e.g., minerals, trace elements, antioxidants, fatty acid profiles, amino acids).
- 16 Projects: Base Diet (e.g., dry matter, protein, fiber, starch, fat, ash, lignin).
- 11 Projects: Safety (e.g., heavy metals, pathogens, contaminants, norovirus).

Research into Greenhouse Gas Emissions

- 11 Projects: Respiration chamber.
- 2 Project: Sulfur hexafluoride (SF6) tracer method.
- 11 Projects: GreenFeed System.
- 5 Projects: Modeling.
- 5 Projects: *In vitro* gas production analysis.

Description of Research	Animal Health & Productivity	Seaweed Analytics	Greenhouse Gas Emissions
Aarhus University *Martin Riis Meisbjerg* Projects include feed value/evaluation, protein value/evaluation, health effects on young animals, effect on methane emissions, and conservation (ensiling) of seaweed.	Growth and production traits Intestinal health.	Health Base diet Safety	Respiration chamber *In vitro* gas production system

Description of Research	Animal Health & Productivity	Seaweed Analytics	Greenhouse Gas Emissions
Agriculture and Agri-Food Canada *Wade Abbott* Structure of seaweed cell walls; glycomic analysis of polysaccharides; protein-carbohydrate interactions; microbial metabolism of complex carbohydrates.		Base diet	
Agriculture and Agri-Food Canada *Wade Abbott, Karen Beauchemin (PI)* Group investigating macro and microalgae native to Canadian waters for anti-methanogenic properties and beneficial effects as animal feed.	Growth traits	Bioactive compounds Base diet	Respiration chamber SF6 tracer method GreenFeed system
Bigelow Laboratory for Ocean Sciences *Aurora M Ricart, Nichole Price (PI)* Investigating the role of farming seaweed in oceanic carbon capture and mitigation of greenhouse gas emissions during the seaweed life cycle.		Carbon and nitrogen analysis	Respiration chamber
Bigelow Laboratory for Ocean Sciences *Nichole Price (PI)* Investigating the possibility of using byproducts from seaweed processors as a feed supplement.	Growth and production traits	Bioactive compounds Health Base diet Safety	
Bigelow Laboratory for Ocean Sciences *David Emerson, Nichole Price (PI)* Microbial impact of seaweed additives on rumen microbiota, specifically methanogens.		Bioactive compounds Safety	
Bigelow Laboratory for Ocean Sciences *Stephen Archer* Investigating the efficacy of seaweed bioactives, including halogenated compounds, to suppress methane production. Runs facility that analyses bioactives and other components of		Bioactive compounds Health	

Description of Research	Animal Health & Productivity	Seaweed Analytics	Greenhouse Gas Emissions
seaweeds for other researchers and customers.			
Blue Ocean Barns *Joan Salwen* Investigating the degradation of bromoform in the rumen.	Growth and production traits	Bioactive compounds Safety	GreenFeed system
Cascadia Seaweed *Jennifer Clark, Kennedy Nikel, Bill Collins (PI)* Identification and subsequent ocean cultivation of temperate species native to the Pacific Northwest that provide relief from bovine enteric methane emissions.	Growth and production traits	Bioactive compounds Health	GreenFeed system
Clarkson University *Susan Powers, Shane Rogers* Lifecycle assessment of the environmental impacts of feeding seaweed and other additives to dairy cow to reduce methane emissions, including (but not limited to) nutrient uptake and kelp harvesting, displaced components of the traditional diet and cow gas emissions.			Modeling
CSIRO and FutureFeed Pty Ltd *Rob Kinley* All aspects of the effect of *Asparagopsis* as a feed ingredient for ruminant livestock (environmental, animal health, and food safety, animal performance, economic viability, seaweed quality and cost of production, commercial scale viability, QA/QC methodology).	Growth and production traits Metabolic diseases	Bioactive compounds Health Base diet Safety	Respiration chamber GreenFeed system Batch and continuous culture
DúlaBio *Danielle Gallagher* Methane reduction in livestock with Irish seaweed.	Production traits	Bioactive compounds Health Base diet Safety	

Description of Research	Animal Health & Productivity	Seaweed Analytics	Greenhouse Gas Emissions
FAO *Camillo De Camillis* Boosting uptake of latest research and novel practices on animal feeding through the FAO LEAP Partnership.			
Ghent University *Olivier De Clerck* Seaweed biology, cultivation, chemical content.		Bioactive compounds	
Greener Grazing *Leonardo Mata* Investigating the potential to farm *Asparagopsis taxiformis* in the ocean, while mastering the production of seedlings onshore.		Bioactive compounds	
Ocean Era, Inc. & National Renewable Energy Laboratory *Lieve Laurens, Simona Augyte, Neil Anthony Sims (PI)* Using the Kyphosid (rudderfish) microbiome as a biological model for biodigestion of macroalgae biomass, with more digestible feedstock as one target outcome and the potential to lead to feed additives.	Growth traits	Health Base diet	
Primary Ocean *Brandon S Barney* Investigating the market demand for seaweed animal health products.	Growth and production traits	Bioactive compounds Health Base diet Safety	
Primary Ocean *Brandon S Barney* Focused on the environmental impacts of seaweed as animal feed in systems that are not "livestock," so chickens, pigs, aquaculture raised fish. Also looking at the genetic, metabolomic and proteomic dimensions of seaweed ecosystems since much of the primary productivity of a giant kelp forest is due	Growth traits		

Description of Research	Animal Health & Productivity	Seaweed Analytics	Greenhouse Gas Emissions
to complex interactions between giant kelp, marine fungi, microorganisms and more.			
Queen's University Belfast *Katerina Theodoridou, Maria Hayes (PI)* Investigating the effect of using seaweeds to 1) reduce methane emissions from dairy cows 2) improve the iodine level of milk 3) reduce ammonia emissions 4) improve protein utilization.	Growth and production traits	Bioactive compounds Health Base diet	Respiration chamber *In vitro* gas production system
Queen's University Belfast *Katerina Theodoridou* Investigating the seasonal variation in the nutritional composition of four Northern Irish brown seaweeds.		Base diet	
Queen's University Belfast *Katerina Theodoridou* Investigating preservation methods for seaweed.		Health Base diet	
Scripps Institution of Oceanography *Jennifer Smith* Team working to optimize growth and bioactive compound concentration in *Asparagopsis taxiformis* with the goal of building pilot and commercial scale cultivation in the US.		Bioactive compounds Health Safety	
Sea Forest, James Cook University *Sam Elsom, Rocky de Nys (PI)* Engaged in advanced stages of R&D and scaling of land and marine based farming, processing, and supply of *Asparagopsis* for inclusion as a feed supplement for ruminants. Working with industry partner trials to address residues in meat and milk products and validating productivity gains at commercial scale in commercial feed systems. With collaborators, quantifying mitigating effects on the production of methane and any concomitant effects.	Growth and production traits	Bioactive compounds Health Safety	

Description of Research	Animal Health & Productivity	Seaweed Analytics	Greenhouse Gas Emissions
Seadling *Simon Davis* Developing fermentation techniques to enhance seaweed for animal feed.	Growth traits	Health	
SINTEF *Inga Marie Aasen* Characterization and processing of seaweed and seaweed components for new applications.		Bioactive compounds Health Safety Polysaccha-rides	
Swedish University of Agricultural Sciences *Mohammad Ramin* Collaborating with projects aiming to identify local seaweeds having potential to reduce methane emission in dairy cows.			GreenFeed system *In vitro* gas production system
Symbrosia *Alexia Akbay* Researching the macroalgae *Asparagopsis taxiformis* as a livestock feed additive for methane reduction. A commercial trial has been completed on a sheep farm.	Growth and production traits Reproductive success Mastitis	Bioactive compounds Health	Modeling Methane laser mini
Teagasc Food Research Centre *Maria Hayes* PI and coordinator of the ERA-NET EU funded project Seasolutions - Mitigation of GHGs using seaweeds in pasture fed sheep, cattle, and dairy cows.		Bioactive compounds Health Base diet	Respiration chamber GreenFeed system *In vitro* gas production system
Teagasc Food Research Centre *Maria Hayes* Project funded by the Irish Government called MethAbate looking for innovative and novel technologies to reduce methane emissions from pasture-based agriculture.		Bioactive compounds Base diet	Respiration chamber GreenFeed system

Description of Research	Animal Health & Productivity	Seaweed Analytics	Greenhouse Gas Emissions
The Seaweed Company *Hilde Vrancken, Stefan Kraan* Investigating the use of proprietary seaweed blends to improve welfare, health, and performance of livestock animals. Methane reduction in cattle is within the scope, but sustainable agriculture is seen as much broader.	Growth and production traits Reproductive success Mastitis Respiratory and metabolic diseases	Bioactive compounds Health Base diet Safety	GreenFeed system
University of California Davis *Ermias Kebreab* Investigating the impact on methane emissions from feeding *Asparagopsis* to dairy and beef cows.			GreenFeed system Modeling
University of California Davis *Matthias Hess* Investigating molecular mechanisms involved in the methane mitigating effect of seaweed with particular focus on changes in function/metabolism of the rumen microbiome.		Bioactive compounds	Respiration chamber GreenFeed system
University of Copenhagen *Hanne Helene Hansen* Investigating 1) the use of minerals from fermented seaweed for calves 2) seaweed degradation and products of fermentation 3) dose response of seaweed derivatives.	Growth traits	Bioactive compounds Health Base diet	*In-vitro* dose response
University of Vermont *Sabrina Greenwood, Nichole Price (PI)* Impact of seaweed on rumen function using bioreactors.			
University of Waikato *Marie Magnusson* Researching cultivation methods for *Asparagopsis armata*.			

Description of Research	Animal Health & Productivity	Seaweed Analytics	Greenhouse Gas Emissions
University of Waikato *Marie Magnusson* Identifying European seaweed with anti-methanogenic properties, in collaboration with Aarhus University, Denmark. Project is called Climate Feed.		Bioactive compounds	
USDA, Agricultural Research Service *Kenneth Kalscheur* Evaluating the effect of a seaweed on lactation performance, rumen fermentation, nutrient digestion, and gas emissions in dairy cow diets.	Production traits	Health Base diet	Respiration chamber
USDA, Agricultural Research Service *Stacey Gunter* Evaluating 27 selections of macroalgae harvested along the California coast as feed additives for methane mitigation.	Production traits	Bioactive compounds	Respiration chamber GreenFeed system
USDA, Agricultural Research Service Investigating the effect of *Asparagopsis taxiformis* on methane production in continuous culture fermenters with forage-based diets and in conjunction with other algae materials (e.g., *Ascophyllum nodosum*).	Growth and production traits		Gas analysis via FTIR analyzer
Washington State University *Kristen Johnson* Investigating manure emissions with seaweed as a treatment.			Respiration chamber SF6 tracer method
Wolfe's Neck Center for Agriculture and the Environment *Leah Puro, Nichole Price (PI)* Investigating the impacts of a dietary seaweed supplement on enteric methane emissions for organic dairy cows.	Production traits	Bioactive compounds Health Base diet	

APPENDIX C
Breakout Session and Workshop Agendas

BREAKOUT SESSION

Productivity and Health Outcomes for Seaweed-Fed Livestock
October 22, 2020 | 11:00am – 1:30 pm EST Virtual Meeting

Overview: Explore the impact of seaweed-based feed ingredients and mechanisms of action on animal performance and productivity, and animal health, to establish shared research priorities.

Desired Outcome: Establish shared research priorities for exploring and optimizing the mechanism and impact of seaweed-based feeds on animal performance and productivity. Secondary outputs would include a list of research priorities relevant to animal health.

AGENDA

10:40 – 11:00 am EST	**Virtual Meeting Room Open** Participants encouraged to log in early and test technology.
11:00 – 11:10	**Welcome and Agenda Review** • Rich Wilson and Meagan Wylie, Seatone Consulting.
11:10 – 11:50	**Panel Discussion:** *Productivity and Health Outcomes for Seaweed-Fed Livestock* Panelists will discuss the impacts of seaweed-based feed ingredients on animal health, performance and productivity, resultant changes to animal microbiome and what that means for methane production, and what animal-related outcomes researchers should be measuring. • Sandra Vijn, World Wildlife Fund. • Matthias Hess, UC Davis. • Juan Tricarico, Innovation Center for US Dairy.
11:50 – 12:05	**Participant Q&A**
12:05 – 12:15	**BREAK**
12:15 – 1:20	**Group Work:** Establish a list of shared research priorities for exploring and optimizing the mechanism and impact of seaweed-based feeds on animal performance and productivity.

	Activity Overview: • Review and refine initial list of research recommendations. • Discuss relative importance of each, associated costs/ study durations, time, likelihood findings would result in positive impacts to animal, etc. • Identify the top 3 to 5 research priorities.
1:20 – 1:30	**Wrap-Up** • Summary of Breakout Session Outputs. • Advancing conversation for the Nov.12th Workshop.
1:30 pm EST	**Adjourn**

Evaluating the Composition of Seaweed for Potential Use in Feeds

October 20, 2020 | 11:00am – 1:30 pm EST Virtual Meeting

Overview: Discuss and define best practices for consistent, comparative evaluation of active compound levels, enzyme activity, potential contaminants, and nutritional profiles in seaweed products using standard protocols.

Desired Outcome: Develop and prioritize a comprehensive list of what can, and needs to, be measured from a livestock and health perspective.

AGENDA

10:40 – 11:00 am EST	**Virtual Meeting Room Open** Participants encouraged to log in early and test technology.
11:00 – 11:10	**Welcome and Agenda Review** • Rich Wilson and Meagan Wylie, Seatone Consulting.
11:10 – 11:45	**Panel Discussion:** *Evaluating the Composition of Seaweed for Potential Use in Feeds.* Panelists will review compounds and nutrients that can currently be measured from seaweeds, if and how this changes by species, season, lifecycle, processing, etc., and discuss seaweed-based livestock feed development research and design. • Nichole Price, Bigelow Laboratory for Ocean Sciences. • Yan Sun, Cargill Animal Nutrition & Health. • Lalitha Gottumukkala, Celignis Analytical. • Steve Archer, Bigelow Laboratory for Ocean Sciences.
11:45 – 12:00	**Participant Q&A**
12:00 – 12:10	**BREAK**

12:10 – 1:00	**Group Work:** Generate a tiered list of bioactive compounds or nutrients that are critical to measure for the purpose of using seaweed as feed. Activity Overview: • Consider an initial list of target analytes under a given scenario. • Apply basic criteria for importance. • Sort analytes into three tiers. • Discuss results.
1:00 – 1:20	**Group Discussion:** Consider methods/techniques that could be applied to measuring top-tier analytes. Share ideas on opportunities for research and development.
1:20 – 1:30	**Wrap-Up** • Summary of Breakout Session Outputs. • Advancing conversation for the Nov. 12th Workshop.
1:30 pm EST	**Adjourn**

Validating Greenhouse Gas Measurements

October 21, 2020 | 11:00am – 1:30 pm EST Virtual Meeting

Overview: Compare and evaluate methods for measuring enteric methane emissions for guiding research and development, informing voluntary carbon markets, and/or for inclusion in IPCC greenhouse gas (GHG) inventories.

Desired Outcome: Examination of the several optional pathways available for measuring enteric methane emissions. Informing the future development of a Best Practices document.

AGENDA

10:40 – 11:00 am EST	**Virtual Meeting Room Open** Participants encouraged to log in early and test technology.
11:00 – 11:10	**Welcome and Agenda Review** • Rich Wilson and Meagan Wylie, Seatone Consulting.
11:10 – 12:00	**Panel Discussion:** *Validating Greenhouse Gas Measurements* Panelist will describe the four different pathways for GHG measurements, discuss the pros and cons/flaws of each method, for which purpose(s) each method is applicable, how methods may or may not be comparable to one another, accuracy and precision of measurements, and levels of acceptability of each. • Tim Kurt, Foundation for Food and Agriculture Research. • Paul Smith, Teagasc The Agriculture and Food Development Authority. • Ermias Kebreab, UC Davis. • Martin Gehrig, TREES Consulting.

12:00 – 12:15	**Participant Q&A**
12:15 – 12:20	**BREAK**
12:20 – 1:05	**Group Work:** Generate foundational information for development of a Best Practices document and/or cheat sheet that describes under "x" scenario, the best method for measuring emissions is "y". Activity Overview: • Propose example scenarios where in one would seek to measure GHG emissions. • Discuss which of the four optional pathways for measuring emissions one could apply. • Determine which method(s) best suited for each scenario.
1:05 – 1:20	**Group Discussion:** Share ideas on opportunities for research and development, new technologies or processes for measuring emissions.
1:20 – 1:30	**Wrap-Up** • Summary of Breakout Session Outputs. • Advancing conversation for the Nov. 12th Workshop.
1:30 pm EST	**Adjourn**

MAIN SESSION

November 12, 2020 | 11:00 am – 4:00 pm EST | Virtual Meeting

Workshop Objectives

- Share and consider report backs from pre-workshop breakout sessions.
- Identify shared interests and priorities to guide research and development.
- Begin to map out the path ahead and develop strategies for effective coordination.
- Consider necessary conditions for successful incorporation of macroalgae into animal feed.

AGENDA

10:50 am EST	**Virtual Meeting Room Open** Participants encouraged to log in early and test technology.
11:00	**Welcome, Agenda Review and Online Platform Protocols** Rich Wilson and Meagan Wylie, Workshop Facilitators.
11:10	**Workshop Purpose and the Potential Path Ahead** • Opening remarks with Paul Dobbins, World Wildlife Fund • Enteric methane: Why do we care? Jack Lewnard, Department of Energy ARPA-E.

11:30	**Report Backs from Pre-Workshop Breakout Sessions** • Productivity and health outcomes for seaweed-fed livestock. • Evaluating the composition of seaweed for potential use in feeds • Validating greenhouse gas measurements. *Objective: Provide an overview of information shared, consider main takeaways, and then discuss unanswered questions and issues linked to each breakout session.*
1:00	**BREAK**
1:30	**A View of Research and Development Linked to Seaweed as Livestock Feed** • Survey results presentation: Ongoing and emerging projects. *Objective: Share pre-workshop survey results and begin building a directory of ongoing and emerging research and development.*
2:00	**Interactive Exercise: The Path Ahead for Seaweed as Livestock Feed** • Opening recap: Shared interests and emerging priorities. • Steps ahead for research and development – what do we know, what still needs to be known and how/when do we coordinate efforts moving forward? • Alternative scenarios for seaweed products and/or enteric methane suppression. • Key considerations for success in the market place. *Objective: Begin to map out the path ahead, determine shared interests and priorities, and identify key considerations for success in the marketplace.*
3:45	**Next Steps and Future Collaboration**
4:00	**Workshop Adjourns**

For almost 60 years, WWF has been protecting the future of nature. One of the worlds leading conservation organizations, WWF works in nearly 100 countries and is supported by more than 1 million members in the United States and more than 5 million globally. WWF's unique way of working combines global reach with a foundation in science, involves action at every level from local to global, and ensures the delivery of innovative solutions that meet the needs of both people and nature. Visit worldwildlife.org to learn more.

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