SORG4NOBAL: Introduction of climate-resilient sorghum for the mitigation of eutrophication and pesticide pollution in the Baltic Sea region

Purpose and aims

Eutrophication and pesticide pollution in the Baltic Sea are clear problems! Intensive agricultural activities around the Baltic Sea are responsible for most of the eutrophication and pesticide pollution of the water system due to the widespread use of synthetic fertilizers (nitrogen, phosphorus, and kalium) and pesticides in farming. According to the updated Baltic Sea Action Plan, eutrophication and pesticides (hazardous substances) continue to pose the greatest threats to the Baltic Sea (Baltic Sea Action Plan – HELCOM). To reach good environmental status regarding eutrophication, the maximum input to the Baltic Sea that can be allowed is 792,209 tonnes of nitrogen and 21,716 tonnes of phosphorus annually (Baltic Sea Action Plan – HELCOM). However, more than 5 million tonnes of nitrogen, 1,4 million tonnes of phosphorus and 1,7 million tonnes of kalium were applied to crop production in the Baltic Sea Neighborhood countries in 2020 (Table 1). In the case of nitrogen, modern cereal crops absorb only 50% of the 5 million tonnes applied (Nitrogen use (in) efficiency in wheat – key messages from 2014-2017 - GRDC), while the remaining is released as N2O or seeps into waterways, causing harmful algal blooms (Retracing cyanobacteria blooms in the Baltic Sea | Scientific Reports (nature.com)). In fact, the same situation can be observed concerning phosphorus and kalium use efficiencies (Phosphorus Efficiency Mechanisms of Two Wheat Cultivars as Affected by a Range of Phosphorus Levels in the Field). Because of modern plant breeding practices, the genes associated with nutrient use efficiency have been lost, resulting in a heavy reliance on synthetic fertilizers for the cultivation of today's crops. Thus, using synthetic nitrogen fertilizers in agriculture and the combustion of fossil fuels has resulted in a doubled amount of reactive nitrogen on Mother Earth. Consequently, such crop production systems contribute significantly to the pollution of the Baltic Sea, leading to eutrophication and dead zones. Yet by 2050, the UN Food and Agriculture Organization predicts that the use of synthetic fertilizers in the world will increase by 50% at the current rate. To reduce eutrophication and pesticide pollution in the Baltic Sea, innovative agricultural best management practices can be used to minimize fertilizer and pesticide applications for crop production. Based on the Baltic Sea Action Plan – HELCOM, the actions addressing eutrophication (E5-E19) and hazardous substances (HL1-HL32) promote sustainable intensification and diversification of crop production. This is also encouraged by the Helsinki Convention (The Helsinki Convention – HELCOM) in order to prevent agriculture pollution using the best available technology and environmental best practices. Sorghum (*Sorghum bicolor*) is an important climate-resilient crop well suited to low input conditions (fertilizers, pesticides, and water), and cultivation of this crop in the Baltic Sea Neighborhood countries could contribute to reducing eutrophication and pesticide contamination. Sorghum's deep roots and large root biomass can contribute to efficient nutrient uptake and soil organic carbon accumulation. In Nordic-Baltic agriculture, sorghum can be introduced to create innovative crop rotation practices that are environmentally and ecologically sustainable, ensuring food, fiber, feed, and bioenergy security while reducing Baltic Sea pollution. The importance of this novel C4 crop lies in its application as a crop rotation tool for improving soil physical and chemical properties, reducing the import of agricultural inputs, diversifying the cropping system, and promoting a circular bioeconomy.

Rationale and significance of the project in the knowledge chain

Eutrophication has been observed in 97% of the Baltic Sea area due to excessive nitrogen and phosphorus inputs in the past and present (Eutrophication – State of the Baltic Sea – Second HELCOM holistic assessment). There is intense algal growth and oxygen depletion on the bottom of the Baltic Sea, resulting in vast areas with anoxic or hypoxic conditions in the basin and adversely affecting the entire ecosystem (Baltic Sea Action Plan – HELCOM). FAO Emissions Shares (FAOSTAT) predicted that synthetic nitrogen fertilizers will be used 50% more globally in 2050 than 2020. More than 60% of global N2O emissions come from agricultural soils, which are directly related to the

application of nitrogen fertilizers to crop production (A gap in nitrous oxide emission reporting complicates long-term climate mitigation | PNAS). Thus, over 70% of global N2O emissions are generated by agriculture, and N2O has a global warming potential of >300 times that of CO2 (Nitrous oxide emissions are enhanced in a warmer and wetter world | PNAS). Indeed, due to the contribution of N2O emissions from agricultural soils to global warming, the Paris Agreement climate target of keeping global warming below 2°C is at risk. With the prevalence of homogeneous crop types (monocultures), disease and pest outbreaks have become more frequent, resulting in the increasing use of pesticides in crop production in the Baltic Sea Neighborhood (Table 2). Such extensive use of synthetic fertilizers and pesticides threatens life below water (SDG14) and life on land (SDG15), which are the main concerns for biodiversity loss, ecosystem services, and natural capital in the Baltic Sea. Thus, the above-mentioned facts prove the importance of implementing sustainable crop intensification and diversification systems to reduce pesticides and fertilizers, particularly by introducing climate-resilient crops like sorghum in the Baltic Sea region. Due to climate change, the resilient and versatile sorghum is expected to become increasingly important in Europe (Sorghum as a Novel Crop for Central Europe: Using a Broad Diversity Set to Dissect Temperate-Adaptation). To our knowledge, sorghum has successfully been cultivated in Denmark (https://www.sorghum-id.com/content/uploads/2018/11/3-challenges-and-genetic-gains-on-forage-sorghum-for-areas-above-48o-latitude-walter-de-miliano-recherche-et-developpement.pdf).

Sorghum is an important versatile C4 crop that serves as a food, feed, and bioenergy crop and a soil fertility enhancer. Importantly, sorghum roots produce exudates that suppress nitrification (Biological Nitrification Inhibition) and denitrification (Denitrification Nitrification Inhibition) processes in the soil, thereby enabling the plant to absorb more nitrogen instead of becoming an environmental pollutant through nitrification, denitrification, leaching, or runoff (Figure 1). Moreover, sorghum exhibits aerial and brace/crown roots above ground, which is essential in acquiring atmospheric nutrients (Figure 2). Sorghum contains high levels of minerals, vitamins, antioxidants, fiber, and protein, preventing a wide range of non-communicable diseases, such as cardiovascular disease, cancer, and type 2 diabetes (Figure 3). The Nordic countries have the highest mortality rate from Alzheimer's disease (Alzheimer's Disease Surging Across Scandinavia - Alzheimer's Disease (alzheimerdisease.tv)). Among natural products, sorghum contains unique polyphenols (Potential of Sorghum Polyphenols to Prevent and Treat Alzheimer's Disease) that prevent and treat Alzheimer's disease (Alzheimer's dementia | Alzheimer Europe (alzheimer-europe.org)). The nutritional properties and health benefits of sorghum make it a novel "well-being" food. Hence, the UN General Assembly has declared 2023 as the "International Year of Millets/Sorghum" to raise public awareness of sorghum's multipurpose properties as a food-feed-bioenergy crop, including its health benefits and use in crop rotation (International Year of Millets 2023 | Food and Agriculture Organization of the United Nations). The introduction of sorghum into the Baltic Sea Neighborhood has the potential to enhance biodiversity and ecosystem services, which aligns with the Baltic Sea Action Plan, EU, and other international action plans.

The overarching aim of this project is to introduce sorghum as a low-input food-feed-bioenergy crop that is capable of building agricultural resilience to climate change and environmental pollution towards reducing eutrophication and pesticide pollution in the Baltic Sea basin. The outcome of this project will contribute to the mitigation of eutrophication and pesticide pollution in the Baltic Sea ecosystem from a land-based perspective.

Project procedure

1) Meta-SWOT analysis of the crop production system in the Baltic Sea Neighborhood and Eastern Partnership countries;

Over the last century, Nordic-Baltic agriculture has been affected by a high degree of crop and landscape simplification: diversity loss has been correlated to a decline in climate resilience and yield stability. Within-field diversity is limited by the prevalent use

of homogeneous crop types, such as pure line varieties and F1-hybrids. As a result, such cropping systems require an excessive amount of synthetic fertilizers and pesticides. As part of this work package, Meta-SWOT (strengths, weaknesses, opportunities, and threats) analyses will be conducted on the current crop production systems in all participating countries (Azerbaijan, Estonia, Lithuania, Sweden, and Ukraine). This Meta-SWOT analysis is based on contemporary national policy documents, government reports, research reports, peer-reviewed publications, etc., relevant to each participating country. Thus, we will be able to identify crop production, crop rotation, and management systems, consequently allowing us to accommodate the cultivation of sorghum in the Baltic-Nordic cropping system. Importantly, sorghum is primarily grown in Azerbaijan and Ukraine for food, fodder, and bioenergy. The Baltic-Nordic countries will benefit from the experience and knowledge of sorghum cultivation and management from Azerbaijan and Ukraine. In August 2023, an inception workshop will be held in Sweden to discuss the Meta-SWOT analysis in each participating country. This Meta-SWOT analysis will provide an overview of current crop production in each of the participating countries, particularly fertilizers and pesticide management for crop production. We will also discuss project implementation, mainstreaming, expected results, and the role of participating researchers and stakeholders at the inception meeting. Participants in the project will exchange information regarding crop production systems and other related issues regarding agriculture in their respective countries.

2) Introduction of sorghum as food-feed-bioenergy crop

Agriculture in the global context requires a new paradigm - new tools and practical innovations to promote sustainable crop diversification and intensification for adaptation to climate change and agroecological practices (Save and Grow - a policymaker's guide to the sustainable intensification of smallholder crop production (fao.org)). As part of the reform of the EU Common Agricultural Policy, guidance has also been provided on sustainable intensification and crop diversification in agriculture (New CAP: 2023-27 (europa.eu)). Introducing new crop species is crucial for enhancing agricultural productivity, increasing product quality, and improving crop resilience to biotic and abiotic stresses. According to the EIP-Agri project 2017-2019 (A Safe and Effective System for Introducing New Crops in Sweden- Sweet Potato as a Case), introducing new crops to the Swedish cropping system is receiving considerable attention, including quinoa (Fagraslätt | Ekologisk växtodling i nordöstra Skåne (fagraslatt.se)), as well in Lithuania (Growing Quinoa in Lithuania- International Year of Quinoa 2013 (fao.org)). Sorghum production in Baltic Sea Neighborhood countries would contribute to alternative food self-sufficiency, better access to quality natural products, and reduced vulnerability along the food supply chain. We have shown promising results for sorghum performance at SLU Lönnstorp Research Station in Lomma over three years. There is also sorghum cultivation in Denmark, Lithuania, and Estonia. This work package aims to demonstrate Sorghum's diverse uses in the Baltic Sea Neighborhood as a food-feed-bioenergy crop. Sorghum products are found in Nordic-Baltic food retail chains, indicating the crop has market potential in the region. Two field demonstration plots will be sown in 2023 at Lomma and Svalöv, and inception workshop participants (in August/September 2023) will visit both sites to assess sorghum's agronomic and physiological performances. Participants will select the best-performing sorghum, and seeds will be sent to each participating country for testing under their local conditions. Once sufficient seeds have been produced, we will conduct a sensory analysis of the best-performing sorghum as part of the ongoing SLU Grogrund project (Searching unique qualities from old and alien cereals for use in conventional and organic breeding | Externwebben (slu.se)). Given its agronomic and physiological characteristics, low input requirements, and diversity of products, introducing sorghum into crop rotation systems is aligned with the Nordic-Baltic Council of Minister's vision for a Green and Competitive Nordic-Baltic Region.

3) Policy and regulation issues related to spreading agrobiodiversity within the food system

Sorghum-based foods are integral to a healthy and nutritious diet that can prevent a wide range of non-communicable diseases, such as cardiovascular diseases, cancer, and type-2 diabetes (Sorghum: Its Unique Nutritional and Health-Promoting Attributes - ScienceDirect). Dietary imbalance and low consumption of whole grains are key factors contributing to global mortality (Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017 - The Lancet). In this regard, sorghum's health-promoting compounds could play an important role in increasing fiber and daily protein intake and thus decreasing global mortality rates (Figure 3). The Swedish Dietary Guideline (Livsmedelsverkets rapportserie), and the European Health Promotion and Disease Prevention Dietary Guideline (Food-Based Dietary Guidelines in Europe | Knowledge for policy (europa.eu)) also recommend sorghum consumption as a whole-grain cereal. Sorghum is a high-protein and nutrient-rich millet crop native to Sudan, Ethiopia, and West Africa, containing all essential health-promoting compounds (Origin, Domestication and Diffusion of Sorghum bicolor - ScienceDirect), and can also be grown in Nordic-Baltic countries. Because of its nutritional properties and health benefits, sorghum is considered a "well-being" food. Therefore, sorghum is receiving increased attention due to its aforementioned advantages, and its production in Europe has been rising significantly over the past few years (EU steps up sorghum promotion in Europe - All About Feed). Hence, the Global Sorghum Conference will be held in Europe to promote sorghum as a food-feed-bioenergy crop (Global Sorghum conference, 2023 (21centurysorghum.org)).

The Helsinki Convention, and HELCOM Baltic Sea Action Plan emphasizes that agriculture is the cornerstone of agrobiodiversity through sustainable intensification and diversification, which is also one of the central component of the EU Green Deal. Achieving green and climate-resilient agriculture requires reaching synergies and managing tradeoffs across the Helsinki Convention, the HELCOM Baltic Sea Action Plan, and other relevant frameworks, including the Paris Agreement, and the Gothenburg Protocol for reducing eutrophication and pesticide pollution in the Baltic Sea. Integrating and harmonizing the above-mentioned policies is essential for protecting the Baltic Sea by ensuring the implementation of best management practices. Moreover, the recent COVID-19 pandemic and Russia's invasion of Ukraine have underscored the need for relocalized food production and consumption. Indeed, the pandemic exposed the vulnerability of our food systems on several levels. This work package aims to raise awareness about spreading agrobiodiversity for making the Nordic-Baltic and Eastern Partnership green towards carbon neutrality and a sustainable, circular, and bio-based economy. Consequently, this will require action on the ground, in collaboration with the Nordic-Baltic-Southern Partnership, using the best available technology and environmental best practices that contributes for reducing eutrophication and pesticide pollution.

4) Outreach, awareness and knowledge sharing

Through press communications, SLU, LAMMC, ETKI, and XXX webpages, citizen science, and other relevant online platforms, the project's objectives and aims will be communicated to the public. The results and findings will be disseminated through Twitter, ResearchGate, LinkedIn, bioRxiv, Google, Slideshare, Zenodo, YouTube, and other online platforms, as well as through public awareness campaigns. We will present our findings in peer-reviewed scientific journals, as well as national and international scientific conferences to reach consumers and growers directly. In Sweden, our project will be presented in the Borgeby Fältdagar 2024, the Cerealier, and ATL Newspapers. OTHER COUNTRIES

5) Project management

The overall project management will be carried out by the SLU. If the project approved, the first virtual (Zoom) kick-off meeting will be held with all project participants. Moreover, we will have a number of virtual (Zoom) meetings to follow up on project activities and implementations. The virtual meeting will be held every three/four months to follow up project activities and implementations, including work plan, risk log, budget,

etc. However, the virtual meeting will be held anytime if requested by the project participants for any project issues and implementations. We will have frequent email communication to update project activities and progress to achieve all project objectives.

Table 1. Fertilizers use in Baltic Sea Neighborhood countries

Country	2000			2010			2015			2020		
	N	P	K	N	P	K	N	P	K	N	P	K
Denmark	234000	36000	79000	180105	32982	62210	225054	33093	63748	232767	37232.75	72936
Estonia	22390	6448	6187	28628	6117	9366	36276	8066	11462	41486	11055	13236
Finland	167000	52000	80000	156523	27000	43168	143479	25172	31372	139316	26272.05	42544
Germany	1847507	351317	543952	1786485	286348	433743	1710616	287762	397759	1265477	192182	446396
Latvia	28498	10217	11574	58643	16150	16288	75820	24354	28659	84346	31241	35724
Lithuania	98000	20000	35000	143200	35000	43000	162813	46244	57179	185779	54513	74632
Poland	895500	317900	401700	1091100	408400	454900	1043000	325900	526500	912000	322000	495000
Russian Federation	960000	280000	180000	1192680	436980	283210	1263420	467890	295680	1916418	686451	478234
Sweden	196716	39042	46724	167194	22387	25288	190228	28602	30688	215171	38110	43652
TOTAL	**4449611**	**1112924**	**1384137**	**4804558**	**1271364**	**1371173**	**4850706**	**1247083**	**1443047**	**4992760**	**1399057**	**1702354**

Source: https://www.fao.org/faostat/en/#data/RFN

Table 2. Pesticide use in Baltic Sea Neighborhood countries

Country	2000	2010	2015	2020
Denmark	3174	3894	2594	3171
Estonia	315	514	594	611
Finland	3608	3807	4919	4913
Germany	35273	40832	48132	48002
Latvia	285	1028	1510	1900
Lithuania	688	1804	2738	2559
Poland	8848	19449	24006	24168
Russian Federation	30194	44305	51360	90535
Sweden	1721	1982	1836	1653
TOTAL	84106	117614	137689	177512

Source: https://www.fao.org/faostat/en/#data/RP

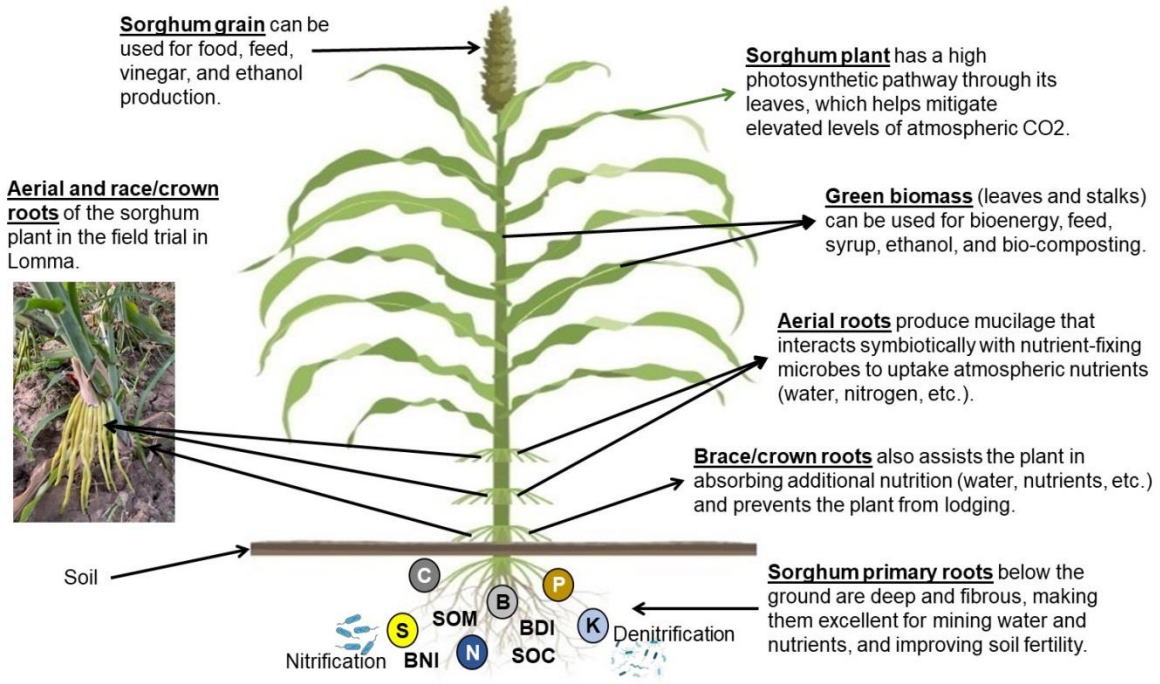

Figure 1. Sorghum plant that can be used for multipurpose benefits

Figure 2. Nutrition and health benefits of sorghum

Table 3. Overall time plan and implementation

Activities	2023					2024												2025							Responsible Person
	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	
Work Package 1. Meta-SWOT analysis of the crop production system in the Baltic Sea Neighborhood and Eastern Partnership countries																									
Gathering information for Meta-SWOT analysis	■																								**All**
Inception workshop in Sweden (SLU Alnarp)		■																							**MR, and All**
Exchange information regarding crop production systems and agriculture activities		■																							**All**
Discuss project implementation, mainstreaming, expected results, etc.		■	■																						**All**
Key milestones: Identify the cropping system used in the Baltic Sea Neighborhood and Eastern Partnership countries					■																				**All**
Deliverables: Report on SWOT analysis					■																				**All**
Wor Package 2. Introduction of sorghum as food-feed-bioenergy crop																									
Field day at Lomma and Svalöv (Sweden)	■																								**MR, and All**
Selection of the best-performing sorghum	■																								**All**
Sensory analysis of the best-performing sorghum			■	■																					**MR**
Field trial in each participating countries										■	■	■	■												**All**
Traveling workshop in Lithuania/Estonia													■												**PP and RA**
Key milestones: Introducing climate-resilient sorghum in the Baltic Sea Neighborhood																							■		**All**
Deliverables: Report on diversification and intensification of crop rotations using sorghum																							■		**All**
Work Package 3. Policy and regulation issues related to spreading agrobiodiversity within the food system																									
Policy review																									**JJ and BK**
Workshop on policy and regulation																			■						**JJ and BK**
Key milestones:																									
Deliverables:																									
Work Package 4. Outreach, awareness and knowledge sharing																									
The press release to the public at the beginning and the of project		■																						■	**MR, and All**
Disseminate the research objectives, aims, and progress through social media and online platforms					■							■					■							■	**All**
Present at the local and international scientific conferences/workshops/meetings etc.														■								■			**All**
Field days (demonstration of sorghum plots to stakeholders and others)	■												■												**All**
Key milestones: Dissemination, list of field days and other events																								■	**All**
Deliverables: Report on outreach, awareness and knowledge sharing																								■	**All**
Work Package 5. Project management strategy and information-sharing mechanism																									
Email communication to update project activities and implementations	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	**MR, and All**
Virtual (Zoom) kick-off meeting with all project participants	■																								**All**
Project follow-up meeting via Zoom with all project participants				■				■				■				■				■				■	**All**
Search and identify relevant funding bodies for formulating poposal																		■	■	■	■	■	■	■	**All**
Final workshop in one of the participating country																								■	**All**
Key milestones: Successful implementation of project activities in all work packages																								■	**All**
Deliverables: Final project report																								■	**MR, and All**

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