博士論文要約（Summary）

入学年 Entrance Year：2021
連合農学研究科
専攻 Course：Resource and Environmental Science of Agriculture, Forestry and Fisheries
氏名 Name：Wijekoon Bandara Mudiyanselage Anushka Chathuranga Bandara

タイトル **Title**	Enhancing Sustainability in Sugarcane Production Via Process-Based Crop Modeling, Fertilizer-Based Emission Mitigation, and A Life Cycle Assessment Approach

キーワード Key word（**APSIM**） （**Gaussian process emulation**） （**Greenhouse Gas Emissions**） （**Life Cycle Assessment**） （**Sugarcane**）

Background of the study

Sugarcane is an important crop for sugar and bioenergy worldwide. However, climate change-mediated spatial and temporal yield variability makes it difficult to manage strategies in the sugarcane sector. Greenhouse gas emissions and non-renewable fossil fuel usage in both sugarcane cultivation and processing phases have raised concerns about the sustainability of the sector. Therefore, the present study focused on comprehensive analysis encompassing process-based crop modeling, optimization strategies, and environmental impact assessments to contribute to enhancing sustainability in sugarcane production in diverse geographic regions, including Khon Kaen, Thailand, Okinawa, Japan, and Sri Lanka.

Process-Based Crop Modeling

Recently, global climate change has affected the agriculture sector more intensely than predicted, and therefore ensuring food security has become more challenging. Climate and weather conditions are the major factors affected by worldwide sugarcane production. In this context, adaptive measures for farming systems while minimizing the costs of negative effects are important. Pressed-base crop modeling provides significant advantages in forecasting and estimation of crop yield under varying environmental conditions and is thereby important in strategy management in crop production.

Cultivar parameterization of process-based crop models is important for achieving high accuracy when estimating crop production under varying environmental and management conditions. However, it is difficult to measure a wide range of parameters practically, and data obtained from field experiments may not be sufficient to parameterize all the varietal information required in modeling. Therefore, it is beneficial to reduce the number of parameters to be calibrated so that resource requirements for measured calibrations can be reduced and over-parameterization during statistical calibration can be avoided. Parameters that are influential but not easily measurable are recognized as ideal candidates to conduct statistical calibration, while parameters that are non-influential or do not have great variation between cultivars remain fixed to default values. Influential and non-influential parameters can be categorized by using sensitivity analysis (SA), while statistical calibration can be achieved through optimization.

Process-based crop models are often computationally expensive, carrying out the required number of simulations may not be feasible, and SA and optimization are extremely time-consuming. Therefore, we evaluated the possibility of using Gaussian process (GP) emulation to reduce the computational burden of SA and optimization with the APSIM-Sugar Model.

In **the first study**, a comprehensive evaluation of the Agricultural Productions System Simulator (APSIM)-Sugar model in Khon Kaen, Thailand, is conducted using global sensitivity analysis based on GP emulation. The study identifies key trait parameters influencing sugarcane dry weight as *radiation_use_efficiency, green_leaf_no, transp_eff_cf, tt_emerg_to_begcane, and cane_fraction* (which explained more than 90% of the total variance on the simulator output), revealing their sensitivity under varying soil types and rainfed and irrigated conditions. The results provide insights for refining modeling accuracy and devising effective management strategies to address temporal and spatial variability in sugarcane yield.

The second study focuses on optimizing cultivar-specific parameters in the APSIM-Sugarcane model for three Thai sugarcane cultivars under rainfed and irrigated conditions. Employing GP emulation and the differential evolution algorithm, the study achieves successful parameterization (validation results between simulated and observed yields: R^2 0.93–0.98; normalized root mean squared error: 5–22%; Willmott's agreement index: 0.87–0.99), yielding simulations closely approximating observed biomass and cane dry weight. This study emphasizes the efficiency of GP emulation in handling computationally expensive simulators, particularly under water-stressed conditions.

Fertilizer-Based Emission Mitigation

Global sugarcane production heavily depends on N fertilizer usage. However, the recovery of N fertilizer by sugarcane is comparatively lower, while most of them are lost to the sugarcane soil system. Losses of N to the soil system could occur via several pathways, including gaseous emissions by microbial conversion of NH_4^+ and NO_3^-, NH_3 volatilization, and NO_3^- leaching.

Nitrous oxide (N_2O) is known to be a powerful greenhouse gas (GHG), and 43% of the total N_2O emission comes from anthropogenic sources, making 52% of it from nitrogen additions in agriculture soil as direct and indirect emissions, including sugarcane soil.

Okinawa is Japan's southernmost prefecture and has inherited a humid subtropical climate. Agriculture plays a vital role in the economy and livelihood of the Okinawan people. Especially related to sugarcane, one of the major crops grown in the region, production has been sluggish because of a labor shortage. Recently, the farming community in the region has moved towards environmentally sound and cost-effective agriculture projects. Therefore, in Okinawa, controlled-release nitrogen fertilizers (CRFs) are promoted to reduce the labor of fertilization (only one-time application is required) and to make fertilizer efficiency high. CRF usage can be considered an efficient way of providing nutrient supply to the crop. However, the influences on the environment from CRFs need to be confirmed, especially related to N_2O emissions under varying environmental and management conditions.

The third study evaluates the ability of controlled-release N fertilizers (CRFs) to reduce N_2O emissions compared to standard N fertilizer in Okinawa, Japan. Laboratory experiments reveal significantly lower N_2O emissions from CRFs (in winter season emission factor [EF]: 0.4% and in spring

season EF: 1.9%) compared to standard fertilizers (in winter season EF: 3.9% and in spring season EF: 4%). Denitrification was more effective at producing N_2O than nitrification during the experiment. The findings underscore the significance of careful fertilizer choice and soil moisture management in mitigating N_2O emissions and nutrient leaching.

GHG Emission and Energy Usage

Recently, many regions of the world are transforming from non-renewable to sustainable renewable energy sources. The sugarcane industry produces a wide range of products and by-products, which can be potentially utilized for bio-based energy production. However, the contribution of the sugarcane production system, especially the sugarcane harvest system, to greenhouse gas emissions is a great concern for sugarcane producers in the context of sustainability.

Life Cycle Assessment (LCA) is a powerful tool that can be used to evaluate potential impacts throughout a product's life from raw material acquisition, processing, manufacturing, use, and finally disposal. LCA can be incorporated to assess the life cycle energy usage and GHG emissions related to the sugarcane industry, which is beneficial for decision-making about the sustainable development of the sector.

The fourth study investigates the Sri Lankan sugar sector's energy usage and GHG emissions using the Life Cycle Assessment approach. A comparison between two major sugar factories established at different time scales highlights variations in energy consumption and GHG emission, with sugarcane cultivation and harvesting phases identified as major contributors to energy consumption [66.5%–73.5%] and GHG emission [62.5%–76.8%]. Both sugarcane factories indicated the highest environmental impact via non-renewable fossil fuel consumption. Enhancing millable cane yield, optimizing machine use, and increasing machine use efficiency were identified as the major phases that should be concerned when achieving the sustainable development of the sugarcane sector in Sri Lanka.

Thesis overview