# 博士論文要約（Summary）

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| タイトル Title | Mitigating Environmental Impact of Sugarcane Cultivation: A Comprehensive Study on Nitrate Leaching from Sugarcane Fields, Water Footprint Assessment, and Process-Based Crop Modeling for Sustainable Utilization of Ground Water Resources.<br>(サトウキビ栽培の環境影響の軽減:サトウキビ畑からの硝酸塩浸出、水フットプリント評価、地下水資源の持続可能な利用のためのプロセスベースの作物モデリングに関する包括的研究。) |
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キーワード Key word（Sugarcane） （Nitrate leaching） （Groundwater contamination）

**Background of the study**

In Okinawa, where highly permeable limestone is distributed, nitrate leaching from sugarcane lands has become a huge problem recently. Therefore, the optimization of fertilizer management practices is crucial for achieving a sustainable balance between agricultural productivity and environmental conservation. There is a need to conduct a comprehensive quantitative assessment of the relationship between applied nitrogen, crop yields, and nitrate leaching characteristics at the field level. In addition, crop modeling plays a crucial role in simulating nitrogen balance in sugarcane fields. While numerous studies have focused on evaluating nitrogen use efficiency in sugarcane to enhance yields, there is a significant gap in research that simultaneously examines the associated nitrogen leaching dynamics. Therefore, this research is focused on addressing this gap to provide insights into the dual aspects of maximizing productivity and minimizing environmental consequences in sugarcane farming through a comprehensive evaluation of nitrogen application practices, and a modeling approach using the APSIMX-Sugarcane to quantify nitrate balance affecting parameters.

**Objectives of the study**

1. To examine groundwater contamination due to nitrate leaching from N fertilizers; urea and controlled-release fertilizers (CRF) via lysimeter field experiments
2. To assess the water footprint of sugarcane cultivation under urea and CRF applications
3. To evaluate the sensitivity of the Key Parameters in the APSIMX-Sugarcane model for nitrate balance

**<u>Examination of the Effectiveness of CRF to Balance Sugarcane Yield and Reduce Nitrate Leaching to Groundwater.</u>**

Although sugarcane cultivation uses heavy fertilization, the maximum recovery of applied N fertilizer is just over 60 % by the crop and soil. Excess fertilizers, especially urea, readily dissolve in soil water causing leaching and runoff and contaminating water resources. CRF can potentially reduce N leaching from cropping systems. CRFs supply nutrients through a single application by controlling the rate and pattern of nutrient release over the crop growth cycle so that frequent fertilization is not required. As nutrient release from CRF is controlled by intercalating fertilizer granules within excipients, the crop nutrient supply can be improved, and environmental and ecological issues are minimized. Although CRF's efficiency has been tested for yield enhancement, there are limited studies on its potential to reduce groundwater pollution. This study focused on field studies aimed at CRF's effectiveness in reducing nitrate leaching.

Two lysimeter field experiments (Exp-1 and Exp-2) spanning both sugarcane plant cane and ratoon seasons were conducted using four treatments: (1) bare land (BL), (2) P and K fertilization without N (N-free), (3) urea, and (4) CRF application in Japan. Meteorological data were collected for the experimental sites. Soil physical and chemical properties were measured for each lysimeter. Underground drainage of the experimental plots was collected at the bottom of the lysimeters, and the percolation water head was calculated. Daily water samples were collected from each lysimeter throughout the experimental period and analyzed for nitrate-N. Growth and harvesting surveys were done and results were compared.

Exp-1 revealed that CRF resulted in higher cane dry weight (CDW) compared to urea in both seasons. In Exp-2, CRF led to higher CDW in the ratoon season than urea and led to lower CDW in the plant cane season compared to urea. Nitrate-N leaching, particularly during the plant cane season of both experiments was lower with CRF than urea demonstrating the environmental benefits of CRF. Conversely, during the ratoon season, nitrate-N leaching was higher with CRF than urea in both experiments, potentially due to increased leaching events that occurred in CRF-treated lysimeters that were influenced by the inherent soil properties. The study emphasized the importance of integrating soil properties with proper fertilizer management practices to achieve a balance between mitigating environmental impacts, conserving groundwater resources, and sustaining realistic sugarcane yields.

**Water Footprint Assessment of Sugarcane Cultivation in Okinawa with Respect to Different Fertilizer Management Practices.**

Addressing the challenges in water resource management, the water footprint assessment provides incentives as an effective tool in the sustainable management of groundwater. It is widely utilized as an indicator that simultaneously assesses the status of water consumption and pollution. The total water footprint of a crop represents the comprehensive assessment of all water used throughout its cultivation process, encompassing the green, blue, and grey water footprints. The green water footprint of the process of sugarcane growing refers to the amount of rainwater consumed or transpired by the crop during its growth and development, while the blue water footprint accounts for the water that is sourced from artificial irrigation. The greywater footprint of sugarcane quantifies the volume of freshwater required to assimilate the load of pollutants released during the process of growing sugarcane. Therefore, to evaluate the potential impact of nitrate-N leaching on groundwater and estimate the crop water productivity under different fertilizer management practices, a water footprint assessment was undertaken involving urea and CRF applications for sugarcane cultivation.

The green and grey water footprints of sugarcane cultivation were estimated by using the data obtained for the urea and CRF treatment applications from the above-mentioned lysimeter field experiments (Exp-1 and Exp-2). As lysimeters avoided surface runoff from agrochemicals, this study only considered the contamination of groundwater via nitrate-N leaching to calculate the grey water footprint. The blue water footprint was not estimated due to zero blue water use in rain-fed conditions. Using the green and grey water footprints, the total water footprint of sugarcane cultivation was estimated. The sugarcane cultivation process from crop establishment to harvesting was set as the boundary condition for water footprint assessment. Direct water use for sugarcane cultivation was considered in the study.

For both crop seasons, in Exp-1 and ratoon season in Exp-2, the total sugarcane water footprint of the CRF application was lower than that of the urea application, indicating the CRF had a lower impact on the groundwater. CRF application in the plant cane season of Exp-2 resulted in a higher water footprint compared to urea, potentially attributed to typhoon damage and the heavy water leaching that occurred with the CRF-lysimeter. The findings of the study highlighted the importance of enhancing green water productivity to minimize the green water footprint and adopting precise fertilizer management practices to reduce the grey water footprint associated with sugarcane farming.

## Global Sensitivity Analysis of Key Parameters in the APSIMX-Sugarcane Model to Evaluate Nitrate Balance Via Treed Gaussian Process.

Process-based crop models are efficient and are widely used to explore the complex nature of interactions among plant growth, soil water, and plant nutrients under various management and environmental conditions. APSIMX-Sugarcane is one of the most widely used platforms for the modeling and simulation of sugarcane production systems. It can be used to evaluate the nitrate balance of sugarcane crop systems and to quantitatively predict nitrate uptake and nitrate leaching by altering each of the important input parameters which aids in addressing the challenges in direct nitrate balance monitoring. Since the crop models are used to conduct simulations under various environmental conditions, it is essential to understand how the sensitivities and uncertainties of input parameters influence the output simulations. Among a large number of input data and parameters used in agricultural simulation models, only a few parameters may strongly affect the output, while the others may have smaller effects. Thus, in a crop model used to evaluate nitrate balance, it is important to identify the influence of different parameters on nitrate uptake and nitrate leaching to reduce the number of parameters required for calibration without affecting model accuracy. Sensitivity analysis (SA) is important in evaluating the effects of changes in input parameters on model performance by quantifying the influence of each parameter on model output variability.

Therefore, a modeling approach was conducted using APSIMX-Sugarcane to quantify the influential parameters on nitrate balance. A treed Gaussian process (tgp)-based global SA was conducted for nitrate uptake and leaching under three conditions: (1) BL: to confirm the influence of soil hydraulic characteristics on nitrate balance in APSIMX-Sugarcane, (2) N-free treatment under radiation use efficiency (RUE) ranges (i) 1.2–1.8 [N-free(a)] and (ii) 1.8–2.5 [N-free(b)], and (3) urea conditions to confirm the influence of fertilizer on nitrate balance in APSIMX-Sugarcane.

The generated meta-models corresponding to each fertilizer level showed good agreements with APSIMX simulators, as confirmed by $R^2$, NRMSE, and AI, indicating that the meta-models could successfully replace the simulators. The most influential parameters (sensitivity indices _ 0.02) were as follows: for leached $NO_3$-N in BL: the parameter related to saturated flow-proportion of water between saturation and field capacity (SWCON) of all soil layers; for $NO_3$-uptake and leached $NO_3$-N in N-free(a) and urea: RUE of the phenological stage (PS) 3 (RUE3) and 4, *tt_emerg_to_begcane*, *green_leaf_no*, and *y_n_conc_crit_leaf* of PS 4 (NCL4); in N-free(b): RUE3, NCL4, and SWCON of soil layers 0–15 cm; 15–30 cm. The outcomes of the study confirmed that the influential parameters in the APSIMX-Sugarcane model of N balance depend on N-stress emphasizing the importance of the model calibrated to obtain accurate model predictions.

**Conclusion**

In conclusion, this research study employed lysimeter experiments, water footprint assessment, and a process-based crop modeling approach to comprehensively evaluate the nitrate leaching characteristics of nitrogen fertilizer in sugarcane cultivation. The research aimed to establish sustainable practices by minimizing nitrate leaching, and consequent groundwater pollution. The lysimeter experiments revealed that the application of CRF would result in lower nitrate leaching. Water footprint assessments indicated that CRF had a lower impact on groundwater compared to urea, reinforcing the need for precise fertilizer management. However, both studies emphasized the importance of considering external factors such as soil fertility conditions, soil physical properties, and weather conditions to ensure reduced leaching from sugarcane fields even under precise fertilizer treatment applications. Overall, both studies identified CRF as the optimal choice for mitigating groundwater pollution, demonstrating its effectiveness in reducing nitrate leaching. The modeling approach identified that the influential parameters in the APSIMX-Sugarcane model for N balance depend on N-stress, and highlighted the importance of calibrating the influential parameters for nitrate balance to improve the accuracy of the model and enhance the efficiency of crop modeling for better nitrogen management.