Optimization of Fertilizer Application and Irrigation to Control Nitrate Leaching

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1. Introduction

In recent years, instances about groundwater pollution from agricultural activities such as chemical fertilizer application to farmlands are at increase in many countries, including Japan. Nitrate leaching to groundwater is then induced mainly by rainfall and irrigation. Thus, an appropriate management of water and nutrient objecting to minimize groundwater pollution and, maximize the nutrient use efficiency and production is desired in an environmentally-sound agriculture.

The major determinants in this problem are the amounts and timings of both fertilizer and water to be applied. The present study aims the optimization of scheduling of fertilizer application and of the amount of water to be irrigated on each day when irrigation is required. This amount of irrigation is decided according to the future occurrence of rainfall in the next following days. The simulation of crop production season is carried out using a model that simulates water, heat and nitrogen cycles in a one-dimensional crop field soil [1].

2. Simulation-Optimization Model

Here, the optimization process is calculated with a combined built-in numerical simulation module, as shown in **Fig.1**. Decision variables (timing and amount of chemical fertilizer application, and amount of irrigation), meteorological data, nutrient uptake pattern by crop and soil parameters are input in the simulation model [1] , providing the amounts of leachate nitrate and water and nutrient deficit for the crop. Those results are input in the optimization model, which searches for the optimum value of the decision variables, with the constraint to minimize crop malnutrition, leaching of nitrate and moisture depletion. This calculation procedure is repeated until a convergence condition is satisfied, and as a result, optimum solution is obtained for the given climate characteristics of the study area and crop's nutrient uptake patterns.

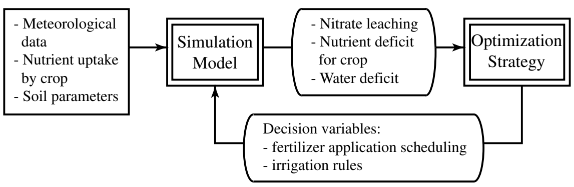

Fig.1 Simulation-optimization model

2.1 Formulation of optimization problem In summary, the optimization problem is resumed into solving the equation

$$\text{Minimize} \sum_{y=1}^{n^y} \int_0^{T_{\max}} (w_1 f_1 + w_2 f_2 + w_3 f_3) \quad (1)$$

where n^y is the number of cropping seasons (years), $T_{\max}$ is the time equivalent to the number of days of a cropping period, w_1, w_2 and w_3 are the weighting factors, f_1 is the outgoing nitrate leaching loss, f_2 is the in-soil nutrients deficit for the crop and f_3 is the in-soil water deficit.

As mentioned before, rainfall and irrigation induce seepage flows, carrying the nitrate to groundwater. To control nitrate leaching, it is easier to do it by controlling irrigation. For example, if rainfall occurrence can be predicted in advance, unnecessary "extra" water is not irrigated, and consequently, undesirable nitrate leaching can be reduced. According to this reason, in the present study, every time when irrigation switch turns "on", i.e., when the pF value exceeds 2.6 at a certain hour of the day (for example, 8:00AM), the rain information of the following next 7 days is obtained, and the decision of how much to irrigate is variated depending on the number of days to the next rain event (d), as shown in **Table 1**. In the case of $d < 1$ (rain event in the next 24 hours, counting from 8:00AM of today), irrigation is not done ($I = 0$), and in the case of $d > 7$ (no rain event for the next 7 days), water amount equivalent to the total readily available moisture (TRAM) is applied. The amounts between those 2 extremes, i_1, i_2 and i_3, are defined by the optimization calculation.

Table 1 Irrigation rule

d [days]	I [mm]
$0 < d \leq 1$	0
$1 < d \leq 2$	i_1
$2 < d \leq 3$	i_2
$3 < d \leq 7$	i_3
$7 < d$	TRAM

The optimization problem is subject to the following constraints, confining daily applied chemical fertilizer and irrigated water, which are the decision variables.

$$F_{\min} \leq F \leq F_{\max} \quad (2)$$

$$0 \leq i_1, i_2, i_3 \leq \text{TRAM} \quad (3)$$

The problem presented above is solved by using genetic algorithms (GAs) [3].

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Table 2 Results for cases STA and OPT

Case	TCF [kgN/ha]	Nitrate Leaching [kgN/ha]		Nutrient Deficit [kgN/ha]		Water Depletion [cm^3/cm^3]		Consumed Water [mm]	
		Average	Deviation	Average	Deviation	Average	Deviation	Average	Deviation
STA	72.0	91.4	16.3	53.1	12.0	0.015	0.007	262.5	129.5
OPT	85.7	72.1	17.5	1.2	3.0	0.018	0.008	132.4	73.9

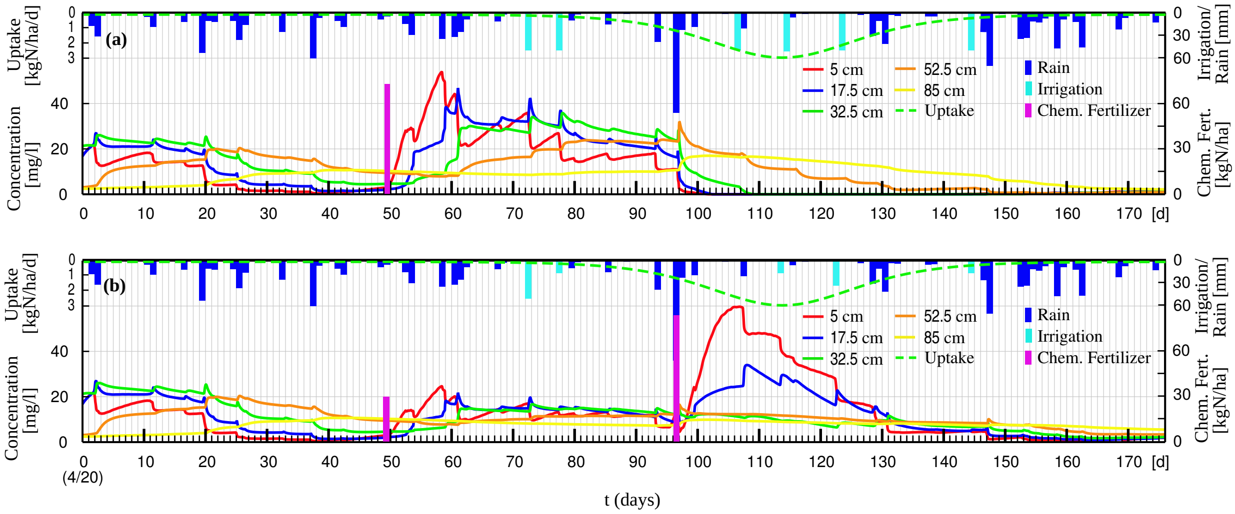

Fig.2 Nitrate concentration for cases (a) STA and (b) OPT

3. Application

The methodology described above is applied to a one-dimensional hypothetical upland soil, with depth of 100 cm and groundwater level at the bottom. The thickness of the effective layer of the soil, for the calculation of TRAM, is considered to be 40 cm, which is equal to the rooting depth of the crop. TRAM value was calculated as 50 mm of water. To obtain solutions that are suitable for different years with variable patterns of rainfall, meteorological data of 28 years (1973-2000) observed at the Nagoya station are used for the optimization.

For comparison purposes, simulation is firstly made with the normal fertilizing practices [3]. According to the authors, 54 kgN ha^{-1} of plants residue is applied to the soil on April 20 (day 0 of simulation), for fertilizing the soil with organic matter. Also as basal dressing, compost of 90 kgN ha^{-1} and chemical fertilizer of 72 kgN ha^{-1} are applied on May 27 (day 38) and June 8 (day 49), respectively. The transplanting of the crop is done on June 9 (day 50), and it is cropped on October 12 (day 176). As for the irrigation, in this case the future occurrence of rainfall is ignored, meaning that the TRAM amount of water is applied to the soil every time irrigation switch turns “on”. This case is defined as the standard scheduling case (Case STA).

For the optimum solution (Case OPT), the only difference in the fertilizer scheduling is that chemical fertilizer basal dressing on June 8 is reduced to 30 kgN ha^{-1} and the top dressing date and amount is obtained by the optimization procedure, which resulted in 85.7 kgN ha^{-1} on July 25 (day 96). For irrigation, the optimum solutions for the amount of water to be applied on each irrigation event were obtained as $i_1 = 16.7$ mm, $i_2 = 25.0$ mm and $i_3 = 33.3$ mm.

It can be readily seen from the results shown in **Table 2** that many problems such as deficit of water and nutrient for the crop and high amount of nitrate leaching is occurring in the standard case, and the optimized solution could effectively control those problems. Even though the amount of total chemical fertilizer (TCF) increased 38% to eliminate crop malnutrition, reduction of 21% in the amount of average nitrate leaching could be observed. To illustrate the simulation in one cropping season, results of year 1998 are shown in **Fig.2**.

4. Conclusion

A simulation-optimization model to obtain optimum fertilizer scheduling and irrigation rules was tested. Satisfactory results were obtained to control nitrate leaching. In this study, the rainfall occurrence used for the irrigation decision was a given variable, as the calculation was made from past data. For the next step, rainfall information based on weekly weather forecast will be used for the decision of irrigation rules, and the applicability of this procedure will be tested.

References [1] Fujiwara, V. S., Takeuchi, J. and Kawachi, T. (2007), 平成 19 年度農業農村工学会応用水理研究部会講演集 , pp.17-23. [2] Goldberg, D. E. (1989), Genetic algorithms in search, optimization, and machine learning. Addison-Wesley Publishing Company, Inc. New York. [3] Kiho, N. and Islam, T. (1995), *Comprehensive Research Reports*, 2, pp.49-63.