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SUMMARY OF DOCTORAL THESIS

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Title:

Improvement of Water and Fertilizer Managements for Enhancing Water Productivity and Net Income of Farmers in Arid and Semi-arid Regions

（乾燥・半乾燥地における
農作物の水生産性と純収益の向上のための水および施肥管理の改善）

With rising water demands due to population growth, the frequency and degree to which the supply of water falls short of its demand will increase as well. In arid and semi-arid regions where the natural rainfall cannot meet the crop water requirement, supplementary irrigation water is suppled to increase yield. However, excessive use of diverted river flows and groundwaters has caused decrease in underwater level and severe environment pollution. In addition, fertilizers have often been overapplied, resulting in lower net income and groundwater pollution. Nowadays, farmers all over the world face rapidly soaring prices of fertilizer. Fertilizer application does increase yield, but with diminishing return. Once maximum yield is achieved, further application would only decrease yield and pollute groundwater. Also, yield response to fertilizer varies with crop, soil type, soil moisture condition, and other limiting factors. The soil moisture and nutrients are two most important factors affecting plant growth and agricultural production, which has interactive effects on plant growth, water use efficiency and nitrogen uptake efficiency. Previous studies have found that stage-based deficit irrigation, subsurface irrigation and alternate partial root-zone irrigation could save water and improve yield. However, little research considering the combination effect of water and fertilizer on crop, especially the effects of spatial soil water and nutrient distribution on water productivity. Also, few studies have focused on the alternative cropping system on water productivity. Therefore, investigations of water and fertilizer coupling have important role in terms of designing high-efficiency, high-yield crop irrigation and fertilization systems that conserve limited resources and are cost-effective and sustainable.

To evaluate the possibility of growing double silage maize with and without film mulch, three years consecutive field experiment was conducted in North China Plain.　In chapter 2, the newly proposed cropping system, double silage maize was compared with traditional system, winter wheat and summer maize. In the view of feasibility of planting double silage maize in NCP, an important plant growth factor, growing degree days, GDD, was considered to assess the possibility of growing double maize. Results indicated that the average GDD in this region is about 2270 °C (>10°C), which is possible for double silage maize but not enough for double edible maize. Although the dry matter of silage maize was not in good quality due to limited growth period, plastic film mulch management increased yield by 16% and 31% in first and second season, respectively. To evaluate the influence of different cropping systems on water use, we employed water footprint, WF, to indicate the water pressure under different situation. Previous studies have shown that the WF of maize was about 0.4-0.6 m^3 kg^{-1}, which is lowest among three staple crops (Mekonnen & Hoekstra, 2010; Hoekstra et al., 2011). In our study, the average total WF of maize silage with mulch was 0.23 and 0.38 m^3 kg^{-1}, and the average total WF of maize silage without mulch was 0.22 and 0.58 m^3 kg^{-1} in the first and second season, respectively. The lower WF of silage maize would present one of the options for sustainable development of agriculture in NCP.

Considering the water consumption and economic returns, the double silage maize saved 160 mm water than traditional WW+SM cropping system, but the net income considering the cost for mulch was lower than the traditional one, which indicated that the proposed cropping system in this study could not improve the net income at the current crop price but diminish the pressure of overdrawn of underground water. The most important thing would be that double silage maize improved the net income per unit water consumption from 0.88 ¥ m^{-3} of traditional to 1.01¥ m^{-3}, which increased the revenue return of water. This implies that if water is volumetrically priced, the practice would enhance net income.

To understand the spatial distribution of water and nutrient on crop growth and yield, in chapter 3, I introduced the study about three different combinations of water and nutrients at two watering levels were set up for winter wheat grown in 1 m deep tubes in 2017/18 and 1.4 m deep tubes in 2018/19 in the field. Supplying fertilizer on surface and water at deep soil gave highest yield and WP at both grain and biomass levels ($WP_{g)}$, under deficit irrigation, with yield 7.7% and 20.9% higher, and WP_g 9.2% and 20.4% higher than NS+WS and ND+WD, respectively. The NS+WS treatment resulted in the highest grain yield and WP at both grain and biomass levels (WP_b) under full irrigation, with yields 17.7% and 31.8% higher, and WP_g 23.4% and 38.0% higher than those of NS+WD and ND+WD averagely for the two seasons, respectively. The differences in yield and water productivity were mainly coming from dry matter allocation. A lower R/S ratio might benefit the partitioning of more dry matter to aboveground biomass to produce higher grain. In this study, fertilizer applied at topsoil profile could increase the availability to plants considering large root system at surface soil. Meanwhile, under deficit irrigation condition, water applied at subsoil could retain relatively higher soil moisture until reproductive stage to provide water for grain filling. In contrast, under full irrigation condition, both water and fertilizer supplied at surface gave optimal combination, which was mainly due to a more efficient root system built under this situation. The lower R/S ratio of NS+WS proved that the plants formed a shallow root system in the water and fertilizer-rich surface soil, thus facilitating the plants to distribute more dry matter to the above-ground parts. This study would provide an example for optimizing spatial management of water and fertilizer under deficit or full irrigation condition in water stressed regions.

Furthermore, farmer-led intensified irrigation is becoming more and more popular, modern technology-controlled irrigation systems are springing up, such as, sensors based automatic irrigation. Such systems require high initial investment, controlling systems and cannot modified irrigation depths according to crop growth process. Therefore, a numerical model to determine irrigation depths which is target with maximum net could be one of the options to save water resources and improve farmers' net income.

In chapter 4, to compare the net income between proposed irrigation scheme and traditional automatic irrigation and refilling irrigation, two-season field experiment of potato was conducted in sandy soil. The proposed scheme determined irrigation depths using WASH_2D model, which is a numerical model of soil water and solute transport and incorporate weather forecast and crop growth. The results indicated that S1 increased potato yield and net income by 19% and 19% compared with A in first season, respectively. Meanwhile, the irrigation water reduced by 28%. In second season, there was no significant difference between S2 and R, which was mainly due to frequent rainfall during potato growth period. Nevertheless, S improved the NU_pE by 39% and 11% compared with A and R, respectively. As for the accuracy of weather forecast, although the rainfall forecast was not in good match with measured one, the comprehensive weather factor, ET_0, was in fair agreement with the value calculated from weather station. It should be noted that the nitrate leaching of the proposed scheme was higher than A and R, this phenomenon come both from the lower water holding capacity of sandy soil and frequently irrigation of S. Higher NU_pE of S helps to reduce the fertilizer input and therefore, to some extent, reduce the nitrate leaching. In conclusion, the proposed scheme combined with weather forecast reduced water use and improved yield and net income compared with other two traditional schemes. This study presented a promising irrigation scheme that could improve net income of farmers and has potential to decrease fertilizer input in future.