

Research Progress on the Impact of Ridge-Furrow Structure Modification in Ridge-Furrow Rainwater Harvesting Cultivation on Crop Growth and Development

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ABSTRACT

In arid and semi-arid regions, limited precipitation with uneven spatial and temporal distribution leads to low and unstable crop yields, which severely restricts the development of local agricultural production. How to efficiently utilize resources such as water, fertilizer, light, and heat in these areas to achieve high and stable agricultural yields and sustainable development is a crucial issue currently facing these agricultural regions. As an efficient water-saving cultivation measure, the ridge-furrow rainwater harvesting (RFRH) technique can effectively alleviate the low utilization rate of precipitation resources, significantly improve the water and heat environment required for crop growth and development, and thus has been widely promoted and applied locally. This paper synthesizes the research progress of RFRH models at home and abroad, summarizes the findings from four aspects: soil water-heat environment, crop photosynthetic characteristics, crop nutrient absorption, and crop growth and development, analyzes the impact of modifying the ridge-furrow structure on crop growth and development under the RFRH model, and provides an outlook on the future development of rainwater-harvesting agriculture in arid and semi-arid regions.

KEYWORDS

Arid and semi-arid regions; Ridge-furrow rainwater harvesting model; Ridge-furrow structure; Crop growth and development

1. INTRODUCTION

With the rapid growth of the global population and the impact of global climate change, the pressure on global food production is increasing day by day. It is projected that the global population will exceed 9 billion by 2050, which will further increase the global demand for food [1, 2]. Arid and semi-arid regions in China play a vital role in agriculture and food production, with arable land area reaching 51 million hectares, accounting for approximately 50% of the country's total arable land [3]. These regions are typical rain-fed agricultural areas. Affected by climatic factors, low and uneven annual precipitation, coupled with limited surface water and groundwater resources for irrigation, result in low and unstable crop yields.

As a cultivation and tillage measure based on precipitation collection, RFRH effectively addresses the scarcity of local agricultural water, improves the utilization rate of limited precipitation, and ensures stable and high crop yields with relatively low input. Therefore, it has been widely promoted and applied in arid and semi-arid regions. With the development of industrial modernization, the RFRH model has also been continuously improved. In particular, the model of covering the ridges with plastic film (based on the traditional ridge-furrow cultivation) has enhanced rainwater harvesting efficiency, increased soil water content, improved soil surface temperature, and effectively promoted crop growth and development [4], forming the current film-mulched ridge-furrow rainwater harvesting cultivation model. However, under the same rainfall conditions, differences in the ridge-furrow structure lead to variations in rainwater-harvesting area and film-mulching area, which inevitably affect the rainwater-harvesting and temperature regulation capabilities of the system, and ultimately impact crop yield and production efficiency. Therefore, designing a reasonable ridge-furrow structure is crucial for the promotion and application of film-mulched RFRH cultivation.

2. IMPACT OF RIDGE-FURROW STRUCTURE ON SOIL WATER-HEAT ENVIRONMENT

Soil moisture and temperature are key environmental factors affecting plant growth and development. The film-mulched RFRH technique combines ridge-furrow cultivation with film mulching for moisture conservation, creating a soil topography with alternating ridges and furrows in the field. The ridges (serving as rainwater-harvesting zones) are covered with plastic film to improve soil temperature and inhibit soil moisture evaporation; the furrows (serving as planting zones) are not mulched, allowing precipitation collected from the rainwater-harvesting zones to be stored in the furrow planting zones, thereby increasing soil water content [5–6].

The effectiveness of the RFRH system is not only related to natural environmental factors such as field precipitation and air temperature but also to the film material used and the ridge-furrow structure itself. The ridge-furrow structure is mainly determined by the width of ridges and furrows and the ridge-furrow ratio (the ratio of ridge width to furrow width). The ridge-furrow ratio determines the proportion of precipitation distribution: due to the anti-seepage effect of the film on the rainwater-harvesting zones, all collected precipitation is concentrated in the planting zones. Within a certain range, a larger ridge-furrow ratio means a higher proportion of precipitation from the rainwater-harvesting zones is diverted to the planting zones. Changes in the ridge-furrow ratio also indirectly alter the film-mulching ratio, thereby affecting the temperature-increasing effect of film mulching.

The width of ridges and furrows determines the amount of precipitation distribution. Within a certain range, increasing the ridge width expands the rainwater-harvesting area, leading to more rainwater collection and a subsequent increase in soil water content in the furrows. However, when the ridge width increases beyond a certain threshold, the increase in soil water content becomes insignificant [7]. A meta-analysis showed that under a high ridge-furrow ratio, the soil water content in the 0–200 cm soil layer increased by 3.40–5.66%, while under a low ridge-furrow ratio, the minimum increase in soil water content was 0.60–1.50% [8].

In arid and semi-arid regions, low temperature during the early crop growth stage is a major factor affecting seed germination and seedling survival rate. The RFRH system can increase the soil surface temperature on the ridges, and this temperature increase is further enhanced to a certain extent as the width of the film-mulched ridges increases. However, the "temperature-increasing effect" has a more significant impact in the early crop growth stage and gradually weakens as the crop grows. Meanwhile, the temperature-increasing effect of a high ridge-furrow ratio is significantly better than that of a low ridge-furrow ratio [9].

3. IMPACT OF RIDGE-FURROW STRUCTURE ON CROP PHOTOSYNTHETIC CHARACTERISTICS

Photosynthesis is a key physiological process through which plants obtain materials and energy for their own growth and development, and it plays a vital role in the accumulation of plant dry matter and the formation of crop yield [10]. Studies have shown that canopy photosynthesis contributes to over 90% of the plant's biomass. As one of the main factors affecting canopy photosynthesis, leaf photosynthesis is the primary driver of dry matter accumulation and organ formation, and serves as the foundation of plant production. Leaf photosynthesis and chlorophyll fluorescence are highly sensitive to abiotic stresses such as water and temperature [11]. Research has demonstrated that improving soil moisture conditions can significantly enhance the photosynthesis, chlorophyll fluorescence, and grain yield of winter wheat [12]. For rapeseed, the RFRH technique increases the net photosynthetic rate, transpiration rate, and stomatal conductance, while reducing the intercellular CO₂ concentration and non-stomatal limitations on photosynthesis—these effects are important reasons for increased crop yield and efficient water use [13].

Canopy structure is a critical factor influencing light distribution and energy acquisition. Enhancing the crop's light acquisition capacity is one of the most important strategies for increasing crop yield [14]. The alternating spatial pattern of ridges and furrows formed by the film-mulched RFRH model optimizes the canopy structure, extends the duration of green leaves, improves light transmittance in the lower part of the canopy, and increases the surface area for light absorption. This allows more light to be reflected to the middle and lower parts of the canopy, effectively enhancing the interception of photosynthetically active radiation (PAR) in the middle and lower plant canopy, improving the overall light-receiving conditions of the plants, and increasing the photosynthetic capacity of individual plants and the photosynthetic rate of the plant population—ultimately leading to increased yield [15–16].

Increasing the width of the film-mulched ridges expands the row spacing between adjacent ridges, which reflects more PAR into the canopy and thereby promotes crop photosynthesis. Conversely, reducing the ridge width (and thus decreasing the row spacing between adjacent ridges) weakens the penetration of PAR into the lower canopy. This may cause premature senescence of leaves in the lower canopy, reduce the leaf area index (LAI), and ultimately affect crop yield [17].

4. IMPACT OF RIDGE-FURROW STRUCTURE ON CROP NUTRIENT ABSORPTION

In rain-fed agricultural areas, in addition to water deficit, nutrient absorption is also crucial for crop growth. Understanding the laws of nutrient migration, accumulation, and distribution in crops is of great significance for developing agricultural production regulation measures. Nitrogen (N), phosphorus (P), and potassium (K) are essential nutrients for crop growth, development, and yield formation, among which nitrogen is absorbed and utilized in the largest quantity [18–19].

Nitrate nitrogen (NO₃⁻-N) and ammonium nitrogen (NH₄⁺-N) are the main forms of nitrogen absorbed by plants. They can directly or indirectly affect photosynthesis by influencing the entire process of plant carbon-nitrogen metabolism. Insufficient nitrogen supply or absorption will limit crop production efficiency and affect yield formation [20]. During the early crop growth stage, nitrogen is mainly concentrated in the leaves; during the reproductive growth stage, organic matter accumulated in the vegetative organs begins to be transported to the grains. The nutrient accumulation in the grains comes partly from the translocation of nutrients in vegetative organs and partly from the direct transport of nutrients absorbed by the roots.

The process of crop nutrient absorption requires water as a medium. Therefore, soil moisture has a significant impact on crop root growth and nutrient absorption, especially nitrogen absorption.

Studies have shown that compared with flat planting (without ridges or furrows), RFRH significantly improves soil water and heat conditions. While increasing the accumulation of crop dry matter, it also promotes nitrogen absorption by crops, increasing the nitrogen accumulation in various plant organs and the total plant nitrogen accumulation [21]. This indicates that RFRH indirectly enhances the absorption and utilization of nutrients by crops.

In RFRH cultivation, as the ridge-furrow ratio increases, the nitrogen absorption by grains also increases. Compared with flat planting, the grain nitrogen absorption under ridge-furrow ratio treatments of 50 cm:10 cm, 80 cm:40 cm, and 60 cm:60 cm increased by 87.0%, 105.1%, and 116.5%, respectively [22, 23]. When the same amount of fertilizer is applied, an increase in crop nutrient absorption implies an improvement in nutrient use efficiency.

5. IMPACT OF RIDGE-FURROW STRUCTURE ON CROP GROWTH AND DEVELOPMENT

In arid and semi-arid regions, RFRH can alleviate the problems of low temperature and insufficient precipitation during spring sowing, synergistically optimize the relationship between vegetative and reproductive growth of crops, shorten the growth cycle, and promote the accumulation of biomass and the formation of crop yield. Compared with flat planting, the RFRH system can shorten the emergence time of maize, promote its vegetative growth, and advance the transition to the reproductive growth stage—this is beneficial for extending the grain filling period and has a positive effect on increasing above-ground dry matter accumulation and maize yield [24, 25].

Increasing the ridge width can enhance dry matter accumulation to a certain extent, possibly because wider ridges increase water supply, thereby promoting dry matter accumulation after flowering. In addition, due to differences in root structure and water absorption characteristics among different crops, the effect of the same ridge-furrow ratio varies across crop types.

Compared with flat planting, increasing the ridge-furrow ratio leads to higher yields of maize and winter wheat. For maize, under ridge-furrow ratio treatments of 40:70 cm, 55:55 cm, and 70:40 cm, the yield increased significantly by 26.1%, 36.4%, and 50.3%, respectively [26]. For wheat, under ridge-furrow ratio treatments of 20 cm:40 cm (R2F4), 40 cm:40 cm (R4F4), and 60 cm:40 cm (R6F4), the yield increased by 51.6%, 109.5%, and 115.2%, respectively [27]. The wheat yield reaches its maximum when the ridge-furrow ratio is 75:50 cm and then decreases. An excessively high ridge-furrow ratio will lead to insufficient water supply for wheat grown on the ridges, producing negative effects that affect wheat heading and grain filling, and ultimately reducing wheat yield [28, 29].

In addition to increasing crop yield, reducing yield variability is another key goal of the RFRH technique. Compared with flat planting, the yield variability of maize under RFRH decreased by 40%, indicating that maize yield is more stable under the RFRH system [30].

6. CONCLUSIONS AND OUTLOOK

In arid and semi-arid regions, affected by local climate, agricultural production faces severe challenges such as water scarcity and insufficient utilization of light and heat resources. As a tillage method to improve local crop productivity, the RFRH model has been increasingly applied to the production of various crops in these regions. RFRH not only improves the soil water-heat environment and provides a favorable growth environment for crops but also promotes the absorption and utilization of soil water and nutrients by crop roots, optimizes the soil water-heat effect, and enhances light use efficiency, nitrogen use efficiency, and economic production benefits.

The effectiveness of the RFRH system is mainly determined by the ridge-furrow structure. The design of the ridge-furrow structure affects the rainwater-harvesting effect and the temperature retention

effect of film mulching, which in turn impacts crop growth, photosynthesis, nutrient absorption, and yield. Modifications to the ridge-furrow structure can regulate the crop population structure: the wide-narrow row planting pattern (resulting from ridge-furrow design) affects the light distribution in the canopy, which further influences the interception of PAR by the canopy. A well-structured canopy is of great significance for the accumulation of photosynthates and the improvement of crop yield.

In arid and semi-arid regions, the practical application of the RFRH technique still faces many problems. Differences in ecological regional climate conditions, soil types, soil moisture status, crop types, and tillage methods all lead to variations in the effectiveness of RFRH. Further research is still needed to determine the optimal ridge-furrow ratio or width.

Currently, global climate change is becoming increasingly complex, and agricultural production is both affected by and contributes to this change. On one hand, under the background of global warming, precipitation uncertainty is increasing, and arid and semi-arid regions will show a trend of "warmer and drier". While improving rainwater-harvesting efficiency during the crop growing season, further research is needed to explore how to utilize precipitation resources during the agricultural fallow period. On the other hand, gases such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emitted during agricultural production are sources of greenhouse gases in the atmosphere. How to meet the demand for grain growth in arid and semi-arid regions while reducing greenhouse gas emissions is the key to addressing climate change and achieving sustainable agricultural development in the future.

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Effects of Different Vegetation Types on Slope Protection in Gully Land Consolidation (DJNY2024-38)

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