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Optimizing Ridge–Furrow Rainwater-Harvesting Strategies for Potato Cultivation in the Drylands of Northwestern China: A Regional Approach

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Abstract: The arid and semi-arid region of Northwest China plays a significant role in potato production, yet yields are often hampered by drought due to limited precipitation and irrigation water. The ridge–furrow rainwater-harvesting technology is an efficient and widely used technique to relieve drought impact and improve crop yield by changing the micro-topography to harvest rainwater to meet the water demand of crops. An analysis of precipitation, water demand, and runoff data spanning 30 years guided the selection of suitable rainwater-harvesting methods tailored to meteorological conditions. The results showed that potato water demand exceeded precipitation in the region. The mulching approach performed best in the western arid region with the most significant increase in yield and water use efficiency (WUE) and was suitable for the western semi-arid region and the agro-pastoral ecotone. In the potato dryland farming areas, the water deficit increased from southeast to northwest. Specifically, northern Gansu, northern Ningxia, and midwestern Inner Mongolia experienced a water deficit of over 200 mm, and rainwater harvesting combined with irrigation was recommended. Conversely, regarding deficits below 200 mm in southern Gansu, Ningxia, and central Inner Mongolia, a 1:1 or 2:1 pattern of ridges could be applied, and mulching was needed only in the necessary areas. For the southern Qinghai, Shaanxi, and eastern Inner Mongolia regions, ridge–furrow rainwater harvesting could be replaced by flat potato cropping. In summary, rainwater harvesting addresses water deficits, aiding climate adaptation in Northwest China's arid and semi-arid regions. The implementation of mulching and ridge–furrow technology must be location-specific.

Keywords: ridge–furrow rainwater-harvesting technology; potato; yield; water use efficiency (WUE); Northwest China

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1. Introduction

In the context of global climate change, extreme drought events have become more frequent and severe, and significant drought events often occur in arid and semi-arid regions. China's arid and semi-arid regions are located in the mid-latitude zone in the hinterland of the Eurasian continent, which is a particularly sensitive area under global climate change. These regions cover approximately 52% of China's cropland and play an indispensable role in China's national food production, especially for potatoes [1]. However, potato growth and production in these regions are significantly constrained by water shortage due to the significantly uneven distribution of precipitation and exacerbated droughts caused by climate warming [2–4]. Annual precipitation in these areas ranges from 300 mm to 380 mm, and more than 60% of precipitation falls between July and September [5]. However, more than 70% of the precipitation is not utilized by crops due to high surface runoff loss. Therefore, it is necessary to adopt appropriate cultivation methods to alleviate the water resource shortage and increase water use efficiency (WUE), thereby improving potato yield in these regions [6].

The ridge–furrow rainwater-harvesting system is a catchment agricultural technology that involves building ridges and furrows in the field [7,8]. Crops are planted in the furrows, and ridges are used to collect rainwater and drain water into ditches [9]. Ridges are usually covered by films to increase runoff and reduce infiltration and surface evaporation (Figure 1). This method allows the planting area to obtain more water and markedly reduces the impact of drought [10]. In agricultural practice, rainwater-harvesting technologies include ridge–furrow planting, ridged mulching furrow planting, ridge–furrow mulching, and other mulching, and are widely applied in the production of crops, such as maize, wheat, oat, potato, cereal, and alfalfa [11–16]. Numerous studies have demonstrated that rainwater-harvesting technology is an efficient approach to improving soil moisture content, WUE, and crop yield. WUE represents the amount of dry matter produced by the evapotranspiration of the unit weight of water in farmland. The WUE of crop field populations is calculated as the yield divided by the water consumption [17]. In recent years, researchers have delved into the optimization of the ratio between ridges and furrows, the selection of mulching materials, and the integration of irrigation technologies, aiming to further enhance the performance of the system. For instance, some experimental simulations and field trials have demonstrated that the ridge–furrow rainwater-harvesting technology, designed based on local precipitation patterns and soil characteristics, can significantly improve the water conditions in the root zone, resulting in a 10–15% increase in water use efficiency (WUE) for potatoes and a yield increase of up to 80% [18–21]. For example, potato fields covered with film usually have an increase of 24.1–69.5% in WUE and 13.6–64.5% [20] in crop yield. Tubers with full mulching showed markedly increased WUE by 56.8–70.3% and yield production by 57.4–78.2% [22]. Therefore, rainwater-harvesting technology has been widely used and played a crucial role in agriculture and grain production in the arid and semi-arid regions of Northwest China.

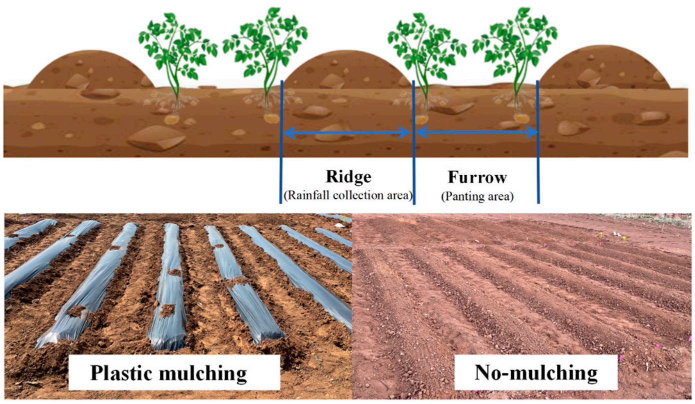

Figure 1. Schematic diagram of the ridge-furrow rainwater harvesting technology.

However, previous studies on rainwater-harvesting technology were mainly based on field experiments that were conducted in a single area and did not evaluate the comprehensive effects of mulching in macro-scale areas [19]. To fill the relevant knowledge gaps and evaluate the effectiveness of different rainwater-harvesting methods over the broad arid and semi-arid regions in Northwestern China, daily meteorological data from the past 30 years were analyzed to explore the appropriate rainwater-harvesting technology for different regions. The objectives of this study were to (1) quantify the water surplus–deficit during the potato growth period at the macro-scale (2) and identify appropriate rainwater-harvesting technologies for different areas in Northwest China based on climatic conditions.

2. Materials and Methods

2.1. Study Area

Northwest China is located in an arid and semi-arid region between 31–48° N and 73–111° E and consists of five provinces and regions, i.e., Shaanxi (31°42′—39°35′ N, 105°29′—111°15′ E), Gansu (32°11′—42°57′ N, 92°13′—108°46′ E), Qinghai (31°9′—39°19′ N, 89°35′—103°04′ E), Ningxia Hui Autonomous Region (35°14′—39°23′ N, 104°17″—107°39′ E), and Xinjiang Uygur Autonomous Region (73°40′—96°18′ E, 34°25′—48°10′ N), with a total area of 310.7 × 10^4 km^2 accounting for 32.8% of China's land area. This arid and semi-arid region has a typical arid and semi-arid continental climate, which is characterized by low and irregular precipitation, high evapotranspiration, and prolonged dry periods.

Inner Mongolia (97°12′—126°04′ E, 37°24′—53°23′ N), extending from Northeast China to Northwest China, is a transition zone between the arid and semi-arid inland region to the northwest and the humid and semi-humid coastal region to the southeast that is affected by the Asian monsoon. The western part of Inner Mongolia has a similar climate to that of Northwest China, and the Inner Mongolia Autonomous Region is sometimes considered part of Northwest China [21], especially western Inner Mongolia.

Since Xinjiang is located in an arid zone, its water resources are mainly replenished by snowmelt and the melting of glaciers or perennial permafrost, and this unique characteristic would have a great impact on the rainwater harvesting studied in this research [20]. Therefore, Xinjiang was excluded from this study, and the following five provinces/regions were selected for study: Shaanxi Province, Ningxia Hui Autonomous Region, Qinghai Province, Gansu Province, and Inner Mongolia Autonomous Region (Figure 2).

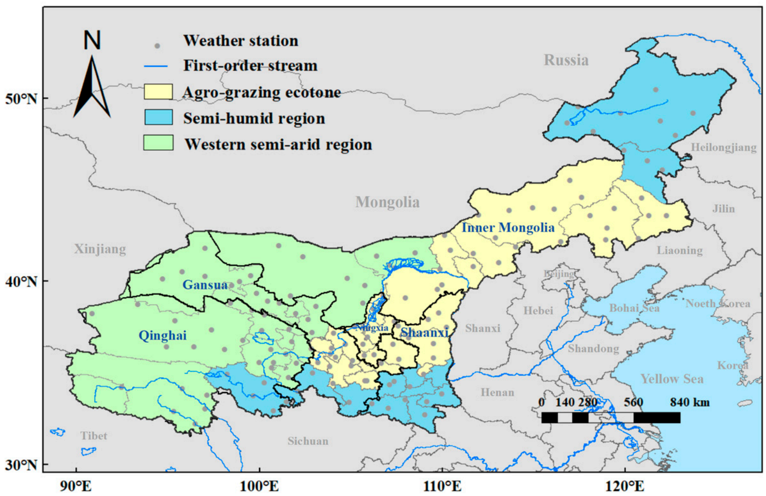

Figure 2. Distribution of meteorological stations in Northwest China of this study.

2.2. Data Collection

In this study, 141 meteorological stations were selected with daily meteorological data records (from 1961 to 2012) including precipitation, sunshine hours, wind speed, maximum and minimum temperatures, relative humidity, and other meteorological elements. All data utilized in this study originate from the official database of the China Meteorological Administration (CMA), where rigorous quality control and calibration procedures are employed to ensure the authenticity and reliability of the data provided. These data were used to calculate the precipitation, water demand, and harvested water using MATLAB R2020b and ArcGIS 10.8 software. The inverse distance weighted (IDW) interpolation method was employed to compute the meteorological variables at regular grid cells to analyze their spatial distributions. The specific goal was to analyze the spatial and temporal evolution characteristics and provide a comprehensive and detailed understanding of the spatial distribution of the precipitation and water deficit in Northwest China.

2.3. Research Methods

2.3.1. Ecological Water Requirement (ET_m)

Crop coefficients (Kc) and reference crop evapotranspiration (ET_0) are widely used to determine the ecological water requirement (ET_m). Kc is a key parameter used in agricultural hydrology and irrigation management that describes the ratio between the water requirements of different crops at different stages of growth and the ET_0 of a reference crop. ET_m stands for Ecological Water Requirement and usually refers to the amount of water required for crop growth through evapotranspiration. ET_0 refers to the ET of grass that is uniform in height, grows actively, and completely covers the ground under optimal soil moisture conditions. The actual evapotranspiration from different crops can be estimated by multiplying the Kc by ET_0, and this value may approximate ET_m in a given case when discussing the water requirements of the whole ecosystem [23]. The Penman–Monteith formula, a recommended standard method by the Food and Agriculture Organization of the United Nations (FAO) for estimating reference crop evapotranspiration, was used to calculate ET_0, and the ecological water requirement of potato (ET_m) is computed as follows [24–27]:

$$ET_m = K_c \cdot ET_0 \quad (1)$$

where ET_m is the ecological water requirement, Kc is the crop coefficient, and ET_0 is the reference crop evapotranspiration. The value of Kc is associated with the fertility stage of the crop, where different fertility stages have different Kc values. In this study, we used specific Kc values of 0.45, 0.80, 1.10, and 0.80 for the different fertility stages of potatoes [28–31]. To determine the growth and fertility periods of potatoes in various regions of the study area, we divided the study area into four regions: eastern (eastern Inner Mongolia), central (central Inner Mongolia, Ningxia, northern Shaanxi, and eastern Qinghai), western, and southern. The associated growing seasons for each region are defined as April–September, May–October, June–October, and May–September, respectively [24,25,29].

The Penman–Monteith formula for ET_0 is given below:

$$ET_0 = \frac{0.408\Delta(R_n - G) + r\frac{900}{T+237}U_2(e_s - e_a)}{\Delta + r(1 + 0.34U_2)} \quad (2)$$

where ET_0 is the daily reference crop evapotranspiration (mm/d), R_n is the net radiation [MJ/($m^2 \cdot d$)], G is the soil heat flux [MJ/($m^2 \cdot d$)], T is the daily average temperature at 2 m altitude (°C), U_2 is the wind speed at 2 m altitude (m/s), e_s is the saturated water vapor pressure (kPa); e_a is the actual water vapor pressure (kPa), Δ is the slope of the saturation vapor pressure versus temperature relationship (kPa/°C), and r is the psychrometric constant (kPa/°C). Soil heat flux and net radiation can be derived from basic meteorological elements [28,30–32].

2.3.2. Runoff Depth (Q)

The water balance equation for a watershed following a rainfall event is given as follows:

$$P = I_a + F + Q \quad (3)$$

where P is the total rainfall (mm), I_a is the initial loss value (mm), F is the subsequent loss value (mm), and Q is the actual runoff volume. I_a includes evapotranspiration, plant retention, infiltration, puddle filling, groundwater recharge, and so on [33].

The SCS model developed by the USDA Soil Conservation Service in 1954 assumed the existence of maximum soil water storage capacity and watershed depression [34], and suggested the rainfall–runoff relationship as follows:

$$F/S = Q/(P - I_a) \quad (4)$$

where S is the maximum detention capacity in the watershed (mm) and is the upper limit of the posterior loss value F [35]. Combining Equations (3) and (4), Equation (5) is obtained as follows:

$$\begin{cases} Q = (P - I_a)^2/(P + S - I_a), & P \geq I_a \\ Q = 0, & P < I_a \end{cases} \tag{5}$$

The value of S varies over a wide range, and the Curve Number (CN) is introduced to determine S:

$$S = 25.4(1000/CN - 10) \tag{6}$$

The CN value varies between 0 and 100 [36] and is a composite parameter reflecting the characteristics of the watershed prior to rainfall. It is related to many factors, such as soil wetness, slope, vegetation, soil type, and land-use practices in the inter-storm period [37].

2.3.3. Ridge–Furrow Ratio

The ridge–furrow rainwater-harvesting technology changes the spatial distribution of precipitation water by altering the micro-topography of the land surface and results in a relatively adequate water supply for the planted area. The ridge–furrow ratio is known as the ratio of the planted area (MP) to the rainwater-harvesting area (MS). In an agricultural field, the ridge–furrow ratio can be calculated according to Equation (7):

$$M_p/M_s = L_p/L_s \tag{7}$$

where Lp is the width of the planted area as a proportion of the total width and Ls is the width of the rainwater-harvesting area as a proportion of the total width. The sum of Lp and Ls is a constant value of 1, as follows:

$$L_p + L_s = 1 \tag{8}$$

Based on the field water balance and the water requirements of potatoes during the growth period, the following equation can be derived:

$$W_0 L_p = \Delta W L_p + P_0 L_p + Q L_s \tag{9}$$

where W_0 is the water requirement during the growth period, P_0 is the effective precipitation, Q is the rainwater harvesting, and ΔW is the changes in effective soil water storage. Combining the above equations, we can obtain:

$$\begin{cases} L_p = Q/(W_0 - \Delta W - P_0 + Q) \\ L_s = (1 - Q)/(W_0 - \Delta W - P_0 + Q) \end{cases} \tag{10}$$

2.3.4. Hydrological Year and Crop Water Surplus–Deficit

Through statistical analysis of the annual precipitation in the study area, three different water-year types were classified: normal year, wet water year, and dry year. A wet year is defined as a year with 20% more precipitation than a normal year, and a dry year is characterized by only 80% of the precipitation of a normal year [38].

Crop water deficit, an indicator that reflects the degree of water deficit in crops, varies considerably during different growth stages and is closely correlated with precipitation and water demand. In order to accurately assess the crop water deficit, it is necessary to calculate the deficit for each growth period, and the equation is shown as follows:

$$SD = R - ET \tag{11}$$

where SD is the surplus–deficit, R is rainfall, and ET is evapotranspiration.

3. Results

3.1. Precipitation, Evapotranspiration, and Surplus–Deficit during Potato Growth Periods

Over the past 30 years, Northwest China experienced significant variations in annual precipitation during potato growth periods (Figure 3). In 2010, precipitation was the highest with 675.9 mm, whereas in 1999, it was the lowest with only 14.5 mm, resulting in a difference of 661.4 mm between the two years. On average, the annual precipitation in the past 30 years was 278.92 mm, with 383.90 mm, 187.90 mm, and 276.34 mm in wet, dry, and normal years, respectively. Spatially, the distribution of average precipitation during the potato growth period in Northwest China exhibits a discernible strip-like pattern, with a gradient of increasing precipitation from northwest to southeast. Specifically, the precipitation in northern Qinghai, northwest Gansu, northern Ningxia, and central-western Inner Mongolia was less than 300 mm, that in southern Qinghai, southern Gansu, central Shaanxi, and eastern Inner Mongolia ranged from 300 to 500 mm, and that in southern Shaanxi exceeded 500 mm with a maximum of 675.9 mm (Figure 3).

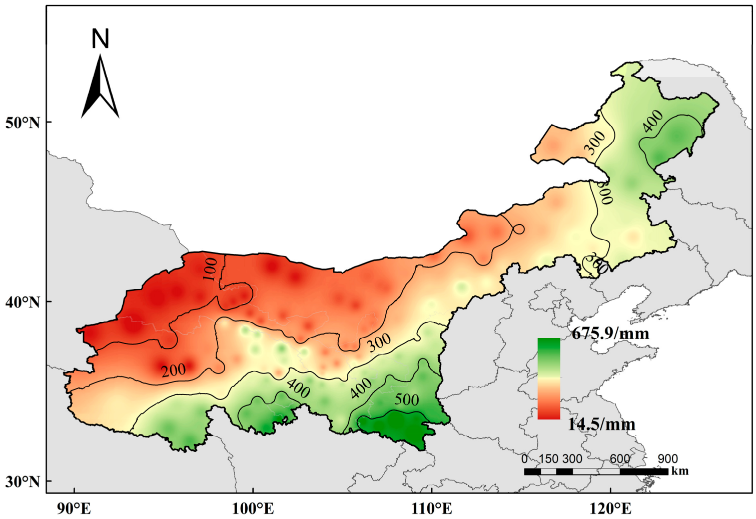

Figure 3. Spatial distribution of precipitation during the potato growth period in Northwest China, 1991–2020.

The evapotranspiration (ET) during the potato growth period in Northwest China exhibited substantial spatial variability, as illustrated in Figure 4. The ET peaked at 724.4 mm in western Inner Mongolia, contrasting sharply with the lowest value of 254.5 mm in eastern Inner Mongolia, yielding a spatial difference of 469.9 mm. Notably, the ET trend was inversely proportional to the southeast–northwest gradient, with lower ET values observed in eastern Inner Mongolia and southern regions of northwest China (<400 mm), moderate values spanning 400–500 mm in central Inner Mongolia, Gansu, northwest Qinghai, and northern Ningxia, and values exceeding 500 mm in western Inner Mongolia. The regional average ET during the potato growth period was 425.13 mm (Figure 4).

Conversely, the spatial distribution of surplus–deficit followed an opposing pattern to ET, with high-ET regions exhibiting negative surplus–deficit characteristics. Overwhelmingly, over 70% of Northwest China was deficient, with a minimum deficit of −682.8 mm. Surplus regions, limited to southern Northwest China and eastern Inner Mongolia, peaked at a maximum of 348.8 mm. The average surplus–deficit stood at −146.2 mm (Figure 4). The integration of precipitation data reveals that regions with higher precipitation tend to exhibit lower ET rates, resulting in water surpluses. However, the overall water demand for potatoes in Northwest China surpasses precipitation levels.

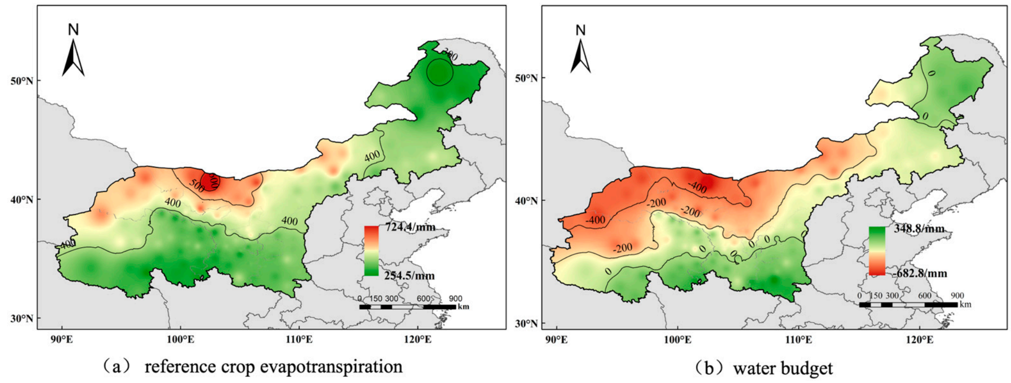

Figure 4. The spatial distribution of reference crop evapotranspiration (**a**) and water budget (**b**) during the potato growth period in Northwest China, 1991–2020. Notes: The water deficit is expressed as the difference between precipitation and reference crop evapotranspiration.

3.2. Relationship between Rainfall and Rainwater Harvesting

Based on precipitation data during the potato growth season in Northwest China, the corresponding water deficit, rainfall collection, and optimal ridge–furrow ratios were calculated. Figure 5 shows that the rainfall collection of mulching was higher than that of non-mulching. For mulching, a 2:1 ridge–furrow ratio was recommended when the precipitation ranged from 190 to 260 mm. For precipitation of 237.7 mm, the water balance point was reached. A 1:1 ridge–furrow ratio could be utilized when the precipitation was between 260 and 400 mm. At precipitation of 316.9 mm, the water balance point was reached. For non-mulching, a 2:1 ridge–furrow ratio was recommended when the precipitation was between 220 and 280 mm. When precipitation was 273.5 mm, the water balance point was reached. A 1:1 ridge–furrow ratio could be utilized when the precipitation ranged from 280 to 400 mm. When the precipitation was 351.5 mm, the water balance point was reached. Under varying conditions of precipitation in Northwest China, the above two planting technologies could satisfy 80% of the water demands during the potato growth period. When the precipitation exceeded 400 mm, flat cropping was recommended (Figure 5).

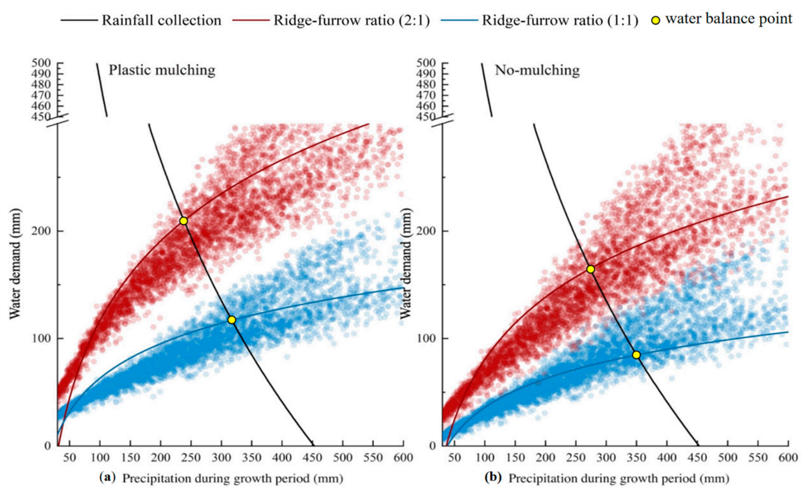

Figure 5. Quantitative relationships between precipitation, water deficit, and rainwater harvesting under plastic mulching (**a**) and non-mulching (**b**) during the potato growth period. (Notes: Water deficit is expressed as the difference between rainfall and evapotranspiration, rainfall collection (2:1) is the amount of rainfall collected when the ridge–furrow ratio is 2:1, rainfall collection (1:1) is the amount of rainfall collected when the ridge–furrow ratio is 1:1, and the water balance point is the point at which the water demand is equal to the rainfall collection at this level of rainfall).

3.3. The Appropriate Rainwater-Harvesting Technology for Different Regions in Northwest China

Based on the comprehensive meteorological data and an evaluation of ridge–furrow rainwater-harvesting technologies, theoretically appropriate field rainwater-harvesting measures tailored to regional characteristics were proposed for potato cultivation in Northwestern China (Figure 6). In the desert areas of northern Inner Mongolia, northwestern Gansu, and northern Qinghai (e.g., Tengger, Badanjilin, Qaidam, and Kubuqi Deserts), annual precipitation below 100 mm determines potato cultivation impractical due to inadequate water availability. In regions with low precipitation and high water demand, including south-central Inner Mongolia, northern Ningxia, and central Gansu, the 2:1 ridge–furrow mulching technology is recommended to enhance water conservation and crop yield. In irrigated agricultural zones, such as the Hetao Plain, Ningxia Plain, and Hexi Corridor, a combination of ridge–furrow mulching and irrigation is advocated to maximize crop productivity. For regions south of the major irrigation zones, encompassing central Qinghai, southern Gansu, southern Ningxia, and east-central Inner Mongolia, a 1:1 or 2:1 ridge–furrow ratio is suggested, with mulching selectively applied in areas where the planting cost can be justified by increased yield. Lastly, in the southernmost regions of Qinghai, Shaanxi, and eastern Inner Mongolia, where conditions are more favorable for crop growth, flat cropping systems are recommended.

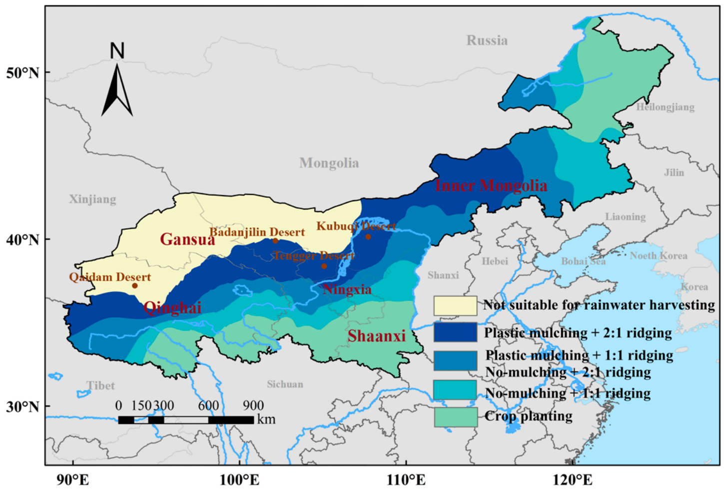

Figure 6. The distribution of ridge–furrow rainwater-harvesting technology in Northwest China.

Based on a comprehensive dataset extracted from 69 published articles on field experiments of rainwater harvesting, a meta-analysis was also carried out in this study to quantify the actual, region-specific impacts of various rainwater-harvesting measures on potato yield in the targeted arid and semi-arid regions of Northwest China. (Figure 7). The results showed that when precipitation ranged from 130 to 300 mm, the yield increase attributed to mulching was the most pronounced, averaging 10.0% to 93.4%, with some areas exceeding 150.0%. In contrast, the yield increase rate under non-mulching conditions initially increased at lower precipitation levels but subsequently declined as precipitation increased. The peak yield increase under non-mulching was observed at precipitation levels of 200 to 380 mm, with an average range of 20.1% to 87.4%.

Overall, the yield increase rate was generally higher for mulching than for non-mulching, with the largest difference observed at precipitation levels below 300 mm. As precipitation increased, the difference in the yield increase rate between the two treatments gradually diminished, becoming relatively small above 500 mm of precipitation.

Based on these findings, we recommend the use of mulching ridge–furrow rainwater-harvesting technology in western semi-arid regions, while both mulching and non-mulching techniques can be utilized in agro-pastoral ecotones. In semi-humid areas, non-mulching ridge–furrow rainwater harvesting technology is favored. These recommendations are based on the unique climatic and agronomic characteristics of each region.

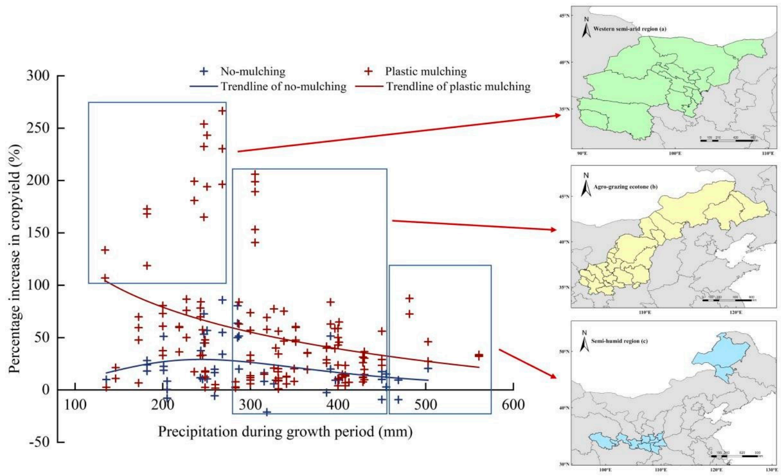

Figure 7. Responses of yield increase rate of potato to ridge−furrow rainwater harvesting under different precipitation levels based on meta-analysis. (Notes: All publications used in the meta-analysis in this study were obtained by searching the Web of Science (http://www.isiknowledge.com/, 15 October 2023) and the China Knowledge Network (http://www.cnki.net/, 15 October 2023). All variables were continuous, and heterogeneity was evaluated using the chi-square test and the I2 test [39–41]. Graphing and meta-analysis were carried out using Python 3.8. According to the diverse geographic and climatic conditions, as well as the naturally cultivated regions of potato in China, the study areas in the meta-analysis were grouped into three geographic regions: the agro-pastoral ecotone, the western semi-arid region, and the semi-humid region. Based on the classification of different rainwater-harvesting technologies, the rainwater-harvesting methods in this study were subject to two main categories: non-mulching and plastic film mulching (short-form mulching), and its effects on potato yield and WUE in the three geographic regions were quantified. In the meta-analysis, 69 publications from 67 sample sites containing 272 yield data and 136 WUE data were compiled into the dataset after searching and screening [42–105]).

4. Discussion

4.1. Cultivation Pattern

The underlying mechanism of ridge–furrow rainwater-harvesting technology in yield enhancement involves the reshaping of micro-topography on the soil surface. This process channels the soil water from the ridges to the furrows, increases the moisture content in the cultivated area, and thereby improves the WUE of crops. Following the analysis of meteorological data, further field data were collected for meta-analysis to validate the results of the refined meteorological data analysis.

In China, ridge–furrow rainwater-harvesting technology was able to increase potato yields by 20.0% to 33.97% and WUE by 33.61% to 37.61%. This result is consistent with the findings in other countries. For example, the adoption of rainwater-harvesting techniques induced a notable augmentation of 60.6% in maize yield in Zimbabwe and increased pepper output by 46.3% in Bafra Plain [102,103]. Mexico experienced a significant enhancement in both total and premium-grade potato yields as a consequence of rainwater harvesting technology [104]. Boers (1982) proposed that the appropriate ratio of catchment area to planting area was a key factor in the effective application of rainwater-harvesting technology [105]. Due to the diverse meteorological conditions in different regions and the varying growth periods of different crops, the optimal ridge–furrow ratio changes accordingly. For instance, the highest yield was attained with a ridge–furrow ratio of 1:1 and a row spacing of 30 cm for the cultivation of fava beans at Matrouh in Egypt [106]. In the semi-arid regions of northwestern China, a ridge–furrow width ratio of 3:2 led to the maximum yield of potatoes concurrently with effectively enhanced WUE [107]. Our results indicated that a ridge–furrow ratio greater than 1 exhibited superior yield and WUE advantages when precipitation during the potato growth period was less than 400 mm. In contrast, a smaller ridge–furrow ratio demonstrated a pronounced enhancement in both potato yield and WUE when precipitation during the growth period exceeded 400 mm.

Secondly, the choice of mulching material was another important factor influencing the soil water retention and crop productivity of rainwater-harvesting technology. Previous results revealed that rainwater-harvesting technology induced a notable increase of 28% in potato yield and a 17% improvement in WUE in the absence of any covering, while it stimulated a substantial rise of 53% in potato yield and an impressive 51% boost in WUE with the application of plastic film coverings. Similarly, complete plastic film coverage led to a substantial increase in potato yield ranging from 57.4% to 78.2%, a notable enhancement in WUE ranging from 56.8% to 70.3%, and a significant improvement in the proportion and quality of large-sized potatoes as compared to the absence of film coverage [21]

In the semi-arid regions of China, water resources are very constrained. To address this limitation, water-saving measurements such as greater ridge–furrow ratios and plastic film covering during the application of ridge–furrow rainwater-harvesting techniques become imperative to augment crop WUE and yield. Despite the notable increase in crop water use efficiency and yield achieved through water-saving measures such as plastic film mulching, these benefits often come at the cost of increased expenses. Consequently, when promoting and applying ridge–furrow rainwater-harvesting technology, it becomes particularly crucial to conduct a thorough analysis and strike a balance between the yield enhancement benefits brought about by film mulching and the additional costs involved. It is essential to adjust the spatial distribution of the cultivation area and select suitable mulching material based on precipitation patterns and crop characteristics during the application of ridge–furrow rainwater-harvesting technology.

4.2. Climate and Climate Change

Water scarcity is a key issue constraining the healthy development of agriculture in arid and semi-arid areas worldwide [108]. Therefore, it is crucial to select suitable rainwater-harvesting measures based on specific climatic conditions. This study aimed to determine the appropriate ridge–furrow ratio and mulch materials for ridge–furrow rainwater-harvesting technology based on regional meteorological conditions, such as the intensity and frequency of precipitation events. The results showed that potato planting in regions with precipitation of 200 mm, such as northern Gansu and western Inner Mongolia, required the use of mulching rainwater-harvesting technology with a large ridge–furrow ratio, but when the precipitation reached 300 mm, such as in the agro-pastoral ecotone of northern China, potato planting could be carried out using non-mulching rainwater-harvesting technology. These results were consistent with the previous research findings of Su et al. [109] and Hu et al. [110].

Several studies have demonstrated there are significant fluctuations in interannual precipitation in the semi-arid regions of northern China [111,112]. We found that the percentages of wet-year, normal-year, and dry-year types in Northwest China from 1991 to 2020 were 57%, 20%, and 23%, respectively. The average precipitation of wet years (92.25 mm) was higher than that of normal years (45.89 mm) and dry years (24.00 mm). This result was in accordance with the findings in the agro-pastoral ecotones [109], and the main reason was that high-intensity rainfall during wet years was more likely to cause runoff. Therefore, it is important to consider the effects of precipitation patterns when selecting rainfall-harvesting technology. This will ensure that the needs of potato growth can be met in 80% of the years, including a few dry years.

The Food and Agriculture Organization of the United Nations (FAO) highlights that climate change will enhance the uneven distribution of precipitation globally, resulting in more frequent droughts that will impact the global food security system [113]. Studies have demonstrated a decreasing trend in both precipitation and crop evapotranspiration in northern China [114]. Additionally, future droughts are expected to worsen [115,116], which will increase uncertainty in rain-fed agricultural production [117]. Therefore, it is necessary to flexibly adjust the adaptability of rainwater-harvesting technology to account for the specific impacts of climate change. In order to improve the water utilization efficiency and ensure the sustainability of agricultural production in irrigated agricultural areas, like Gansu and Ningxia, rainwater-harvesting techniques for ridges should be more closely integrated with irrigation techniques, such as drip irrigation and rainwater-harvesting ponds. In the agro-pastoral ecotones, a transition from non-mulching planting to mulching planting is recommended to reduce soil moisture loss and increase WUE. In southern Gansu and southern Ningxia, it is proposed to increase the ridge–furrow ratio to improve the rainwater-harvesting efficiency per unit area.

In summary, developing a high-yield and high-efficiency potato cultivation model in the northwest and implementing locally adapted measurements to address climate change in each region are crucial for improving WUE and promoting the sustainable development of the potato industry. This will not only aid in agricultural adaptation but also make a positive contribution to wider agricultural sustainability and ecological health.

5. Conclusions

Based on meteorological data, this study conducted an in-depth analysis of the spatiotemporal change patterns of potato water requirements and water shortages during potato growth periods in Northwest China over the past 30 years and developed a high-yield and efficient potato cultivation model for determining appropriate rainwater-harvesting technologies for different areas. The results suggested that the adoption of rainwater-harvesting technology should be site-specific. There are also some limitations in this study due to the fact that the analysis was based on a 30-year meteorological data record and the selected meteorological observational sites were in Inner Mongolia and Qinghai. In addition, since the growing season of potatoes is expected to extend with the warming of the climate, the water requirements calculated in this study may be an underestimation. Therefore, future research should involve comprehensive, long-term studies across multiple experimental sites. While this article delves into the impact on yield and water use efficiency, it lacks a comprehensive examination of the economic benefits stemming from yield enhancement and the cost analysis of plastic film mulching. These aspects will constitute the primary focus of subsequent analysis. Furthermore, the significance of rainfall distribution patterns during the potato-growing season on crop development and yield, as well as the crucial role of mulching in regulating potato field temperatures, cannot be overlooked and will be further analyzed in future studies.

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