Simulation Study on the Response of Potato Growth, Development and Yield to Drought Stress in the Single-Cropping Region of North China: A Case Study of Wuchuan County (Postprint)

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Abstract

To investigate the effects of different degrees of drought stress on potato growth, development, and yield in the single-cropping region of North China, taking Wuchuan County, Hohhot City, Inner Mongolia as an example, the APSIM-Potato model was calibrated and validated based on multi-year potato growth and development data and meteorological data to evaluate the model' s applicability in the Wuchuan region. The validated model was used to simulate the responses of potato leaf area index (LAI), above-ground biomass, and yield to drought stress at different developmental stages. The results showed that: (1) The root mean square error (RMSE) between simulated and observed values for the duration of each developmental stage was within 3 days; the normalized root mean square error (NRMSE) between simulated and observed values for LAI, above-ground biomass, and yield was 12.82%, 17.35%, and 14.48%, respectively, all below 20%, indicating that the APSIM-Potato model has good applicability in the Wuchuan region.

(2) With increasing duration and intensity of drought stress, potato LAI, above-ground biomass, and yield decreased accordingly. When simulating drought stress at a single developmental stage, potato LAI, above-ground biomass, and yield showed the greatest response to water stress during the branching-flowering stage; when simulating continuous developmental stage drought stress, LAI, above-ground biomass, and yield showed the greatest response to water stress during the entire growth period.

Simulation of Potato Growth and Yield Response to Drought Stress in the Single-Cropping Region of Northern China: A Case Study of Wuchuan County

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Abstract

To investigate the effects of varying degrees of drought stress on potato growth, development, and yield in the single-cropping region of northern China, this study takes Wuchuan County in Hohhot City, Inner Mongolia as a case study. Based on multi-year potato growth data and meteorological observations, the APSIM-Potato model was calibrated, validated, and evaluated for its applicability in the Wuchuan region. The validated model was then employed to simulate potato responses in leaf area index (LAI), aboveground biomass, and yield under drought scenarios at different developmental stages. The results demonstrate: (1) The APSIM-Potato model exhibits good applicability in Wuchuan County, with normalized root mean square error (NRMSE) between simulated and observed values of LAI, aboveground biomass, and yield all below 20%, and determination coefficients (R^2) and consistency index (D-index) all above 0.85. (2) As drought stress duration and intensity increase, potato LAI, aboveground biomass, and yield decrease accordingly. Under single-stage drought stress, the branching-flowering stage shows the greatest response, with LAI, aboveground biomass, and yield decreasing by 3%-33%, 17%-35%, and 2%-25%, respectively. Under continuous-stage drought stress, the entire growth period shows the most significant impact, with LAI, aboveground biomass, and yield decreasing by 10%-57%, 29%-69%, and 55%-75%, respectively, while the time required to reach maximum LAI and aboveground biomass is delayed by 10-17 days and 13-18 days, respectively. These findings provide a theoretical foundation for analyzing APSIM-Potato model applicability in northern China’ s single-cropping region and for in-depth investigation of drought impacts on potato production under climate warming.

Keywords: potato; APSIM-Potato model; applicability evaluation; drought simulation; leaf area index (LAI); biomass; yield

Introduction

Against the backdrop of climate change, population growth, and decreasing arable land, enhancing China' s grain production and achieving sustainable agricultural development have become critical research priorities. As the world' s fourth-largest food crop, potato is widely distributed, highly adaptable, and offers substantial yield potential, making it one of the most promising non-cereal crops. To ensure national food security and promote sustainable agricultural development, China has advocated for processed potato as a staple food and launched the "potato-as-staple-food" strategy. Potato is a typical temperate climate crop that is highly sensitive to water availability, with water being the primary abiotic factor limiting potato yield across most regions of China. The single-cropping region in northern China, characterized by abundant sunshine, cool climate, and large diurnal temperature variations, represents one of the country' s major potato-producing areas. However, most of this region lies in the agro-pastoral ecotone, where water and land resources are scarce and vulnerability to natural disasters is high, leading to widespread issues such as low proportions of high-quality varieties and suboptimal per-unit yields.

Current research on drought impacts on potato in China primarily combines field experiments with statistical analysis, employing artificial water control in experiments to investigate how different water conditions affect potato morphological characteristics, physiological-biochemical indices, and yield quality. These studies have provided technical parameters and theoretical foundations for selecting cultivation techniques and optimal irrigation timing in potato production. However, field water control experiments often struggle with precise water management, and sampling representativeness is susceptible to human factors, making it difficult to dynamically simulate water stress scenarios throughout potato growth and development or to adequately simulate and analyze potato climatic production potential.

Crop growth models, compared with field experiments and statistical methods, use environmental driving variables such as light, temperature, water, and soil conditions to quantitatively describe relationships between crop status variables and environmental/technical conditions. These models offer clear advantages in assessing and predicting climate change impacts on crop growth and yield, and have become efficient tools for supporting agricultural production decisions. The Agricultural Production Systems Simulator (APSIM) is a mechanistic model developed by Australia for simulating biophysical processes in agricultural production systems. Since its introduction to China, extensive calibration and validation work has been conducted across various regions, demonstrating its effectiveness in guiding local production of potato, wheat, and other crops.

Wuchuan County is an important potato-producing area in the single-cropping region of northern China. This study selects Wuchuan as the research area and "Kexin No. 1" as the study variety. Based on multi-year potato growth data and meteorological observations from Wuchuan, the study evaluates APSIM-

Potato model applicability in the region and analyzes potato LAI, aboveground biomass, and yield responses to different drought scenarios.

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1 Materials and Methods

1.1 Study Area

The study area is Wuchuan County, Hohhot City, Inner Mongolia, located in central Inner Mongolia (40°47 -41°23 N, 110°31 -111°53 E), with a total area of 4,886 km^2. The region has a temperate continental monsoon climate and is a typical semiarid dryland agricultural zone. Annual average precipitation is approximately 360 mm, concentrated in June–August and accounting for about 70% of the total growing season precipitation. Annual evaporation is approximately 5-6 times the precipitation amount, the frost-free period is 90-120 days, and soils are primarily chestnut soil type.

1.2 Data Sources

Meteorological data: Daily meteorological data for Wuchuan County from 1986–2020 (maximum temperature, minimum temperature, precipitation, sunshine hours) were obtained from the National Meteorological Science Information Network ground meteorological observation dataset.

Crop data: Potato variety information, field management practices, growth stages (sowing, emergence, branching, flowering, and harvest), aboveground biomass, and yield data for the study area in Wuchuan County from 2015–2019 were obtained from the Wuchuan Agricultural Environment Science Observation Station of the Ministry of Agriculture in Hohhot, Inner Mongolia, the Wuchuan County Statistical Yearbook, and related literature.

Soil data: Soil data for Wuchuan County were obtained from the *Chinese Soil Species Records*, *Inner Mongolia Soil Yearbook*, *Wuchuan County Records* (continued edition), and related literature. Specific soil parameters are shown in .

1.3 Model Description and Validation

1.3.1 APSIM-Potato Model Overview This study selected the APSIM-Potato model (version 7.10) to simulate potato LAI, aboveground biomass, and yield responses to drought stress scenarios at different developmental stages. APSIM is a process-based crop growth model that integrates crop modules with other modules through a central engine, more intuitively representing relationships between crop growth processes and environmental/technical conditions. The APSIM-Potato model divides potato development into eight stages: sowing, sprouting, emergence, flower bud differentiation, tuber formation, flowering, senescence, and maturity. In this study, following agricultural meteorological observation standards, model developmental stages were matched to actual potato production stages: sowing-emergence, emergence-branching, branching-flowering, and flowering-harvest. Average typical dates for each developmental stage in the study area are shown in .

The model controls developmental stage length through different mechanisms: the sowing-to-sprouting duration is controlled by sowing depth, soil moisture, and soil temperature, while other stages are controlled by accumulated temperature and photoperiod. Key cultivar parameters controlling potato growth and development in APSIM-Potato include: photoperiod after emergence, effective accumulated temperature from sowing to emergence, effective accumulated temperature from emergence to tuber maturity, effective accumulated temperature from tuber formation to maturity, and maximum specific leaf area. Effective accumulated temperature refers to the sum of effective temperatures during a developmental stage, i.e., the cumulative sum of daily mean temperature minus the biological lower limit temperature.

1.3.2 Solar Radiation Calculation The APSIM-Potato model requires daily solar radiation input, which was converted from sunshine hours using the Angstrom-Prescott formula:

$$Q = Q_0(a + b\frac{n}{N})$$

where Q is daily total solar radiation ($\mathrm{MJ \cdot m^{-2}}$); a and b are empirical coefficients related to atmospheric conditions; n is daily sunshine hours (h); N is daily possible sunshine hours (h); and Q_0 is extraterrestrial radiation ($\mathrm{MJ \cdot m^{-2}}$), calculated as:

$$Q_0 = \frac{1440}{\pi} I_0 \rho^2 (\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s)$$

where I_0 is solar constant; ρ is relative Earth-Sun distance; ω_s is sunrise hour angle (°), calculated as $\omega_s = \arccos(-\tan\phi \tan\delta)$; ϕ is geographic latitude (°); and δ is solar declination (°).

1.3.3 Model Calibration, Validation, and Evaluation Metrics During model calibration, the goodness-of-fit method was used to compare differences between simulated and observed data to find optimal parameter combinations and determine cultivar genetic parameters. During validation, graphical comparisons and statistical metrics were used to evaluate model applicability. Statistical indicators included: root mean square error (RMSE) and normalized root mean square error (NRMSE) to reflect relative and absolute errors; and coefficient of determination (R^2) and consistency index (D-index) to reflect agreement between simulated and observed values.

RMSE and NRMSE were calculated as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i)^2}$$

$$NRMSE = \frac{RMSE}{\bar{X}} \times 100\%$$

where n is total sample number; Y_i and X_i are simulated and observed values, respectively; and $\bar{X}$ is the mean of observed data. Validated cultivar parameters are shown in .

1.4 Baseline Year Selection

Based on 1986–2020 meteorological data for the study area, multi-year averages of mean temperature and total sunshine hours during the entire growth period were calculated. Years with temperature and sunshine hours near the average but with distinctly different precipitation were selected, assuming that yield variations in these years were primarily caused by precipitation differences. As shown in [Figure 1: see original paper], the selected years had temperatures and sunshine hours near the average but substantially different precipitation. In these years, simulated yields showed approximately 60 mm differences, with yields varying significantly with precipitation. Among these, 2018 was the highest precipitation year (approximately 460 mm). Therefore, this study selected 2018 as the baseline year, with precipitation gradients set at 60 mm intervals for drought scenario design.

1.5 Drought Scenario Design

1.5.1 Drought Scenario Setup Based on Wuchuan' s meteorological conditions and local 实际情况, the baseline year and precipitation gradients were selected for drought simulation. Using the baseline year as the control (CK), precipitation during each potato developmental stage was proportionally altered to establish drought scenarios from mild to severe (Table 4). For single-stage drought stress, precipitation from different drought years for a specific developmental stage replaced the corresponding stage precipitation in CK. For continuous-stage drought stress, precipitation from two or more consecutive developmental stages from different drought years replaced the corresponding stages in CK. This study employed continuous simulation scenarios without soil water reset at the beginning of each annual simulation. Under all drought scenarios, conventional local management practices were adopted: planting density of 55,000 plants · hm^{-2}, row spacing of 40 cm, and sowing depth of 10 cm. The automatic fertilization module in APSIM-Potato was configured to apply nitrogen fertilizer automatically when soil nitrate nitrogen content in the 0–60 cm layer fell below 50 kg · hm^{-2}, ensuring no nitrogen stress during potato growth.

1.5.2 Potato Yield Reduction Rate Based on drought scenario settings, drought conditions were specified in the model to simulate dry matter yield under each scenario. When comparing with observed fresh tuber yield, dry weight was converted to fresh weight assuming 80% water content. Yield reduction rates under different drought scenarios were calculated as:

$$D_t = \frac{Y_{t,CK} - Y_t}{Y_{t,CK}} \times 100\%$$

where D_t is yield reduction rate in year t (%); $Y_{t,CK}$ is simulated yield under normal meteorological conditions in year t ($\mathrm{kg \cdot hm^{-2}}$); and Y_t is simulated yield under drought conditions in year t ($\mathrm{kg \cdot hm^{-2}}$).

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2 Results

2.1 APSIM-Potato Model Applicability Analysis

2.1.1 Applicability for Simulating Potato Growth Stages Using observed data for potato developmental stages in the study area, the APSIM-Potato model' s suitability for simulating Wuchuan potato phenology was validated. Results showed that under these cultivar parameters, the model simulated Wuchuan potato growth stages well. The RMSE between simulated and observed days for emergence, branching, flowering, and harvest stages was within 3 days, with R^2 and D-index both above 0.85, indicating good model performance.

2.1.2 Applicability for Simulating Potato LAI, Aboveground Biomass, and Yield Comparisons between simulated and observed values of potato LAI, aboveground biomass, and yield are shown in [Figure 4: see original paper]. For LAI, simulated values were slightly higher than observed values, with NRMSE of 12.82% and R^2 and D-index of 0.88 and 0.94, respectively. For aboveground biomass, NRMSE was 17.35%, with R^2 and D-index of 0.90 and 0.95, respectively. For yield, NRMSE was 14.48%, with R^2 and D-index of 0.87 and 0.94, respectively. These results indicate that the model can satisfactorily simulate potato LAI, aboveground biomass, and yield in Wuchuan County.

2.2 Potato Responses to Water Stress at Different Developmental Stages

2.2.1 Potato LAI Response to Water Stress at Different Stages Single-stage drought stress simulations ([Figure 5: see original paper]) and continuous-stage drought stress simulations ([Figure 6: see original paper]) were conducted using experimental group precipitation for four single stages and six combined stages to replace corresponding precipitation in CK. Under single-stage drought stress, potato LAI decreased with increasing drought intensity. At the same drought intensity, LAI response to water stress at single stages ranked from largest to smallest as: branching-flowering, emergence-branching, flowering-harvest, sowing-emergence. Among these, branching-flowering stage water stress had the greatest impact, reducing LAI by 3%-33% compared with CK, while sowing-emergence stage water stress had the smallest impact (1%-26% reduction).

Under continuous-stage drought stress, LAI decreased with increasing drought intensity and duration. At the same drought intensity, LAI response to continuous-stage water stress ranked from largest to smallest as: sowing-harvest, emergence-harvest, sowing-flowering, emergence-flowering, branching-harvest, branching-flowering. The sowing-harvest (full growth period) water stress had the greatest impact, reducing LAI by 10%-57% and delaying the time to reach maximum LAI by 10-17 days. The branching-flowering stage water stress had the smallest impact (1%-38% reduction).

2.2.2 Potato Aboveground Biomass Response to Water Stress at Different Stages Under single-stage drought stress, aboveground biomass decreased with increasing drought intensity. At the same drought intensity, aboveground biomass response to single-stage water stress ranked from largest to smallest as: branching-flowering, emergence-branching, flowering-harvest, sowing-emergence. Branching-flowering stage water stress had the greatest impact, reducing aboveground biomass by 17%-35%, while sowing-emergence stage water stress had the smallest impact (5%-11% reduction).

Under continuous-stage drought stress, aboveground biomass decreased with increasing drought intensity and duration. At the same drought intensity, aboveground biomass response to continuous-stage water stress ranked from largest to smallest as: sowing-harvest, emergence-harvest, sowing-flowering, emergence-flowering, branching-harvest, branching-flowering. Full growth period water stress had the greatest impact, reducing aboveground biomass by 29%-67% and delaying the time to reach maximum biomass by 13-18 days. The sowing-branching stage water stress had the smallest impact (9%-37% reduction).

2.2.3 Potato Fresh Tuber Yield Response to Water Stress at Different Stages Single-stage drought stress simulations ([Figure 7: see original paper]) and continuous-stage drought stress simulations were conducted. Under single-stage drought stress, yield decreased with increasing drought intensity. At the same drought intensity, yield response to single-stage water stress ranked from largest to smallest as: branching-flowering, emergence-branching, flowering-harvest, sowing-emergence. Moderate water reduction during sowing-emergence actually increased yield by 1%-9%. Branching-flowering stage water stress caused yield reductions of 3%-50%, while flowering-harvest stage water stress caused reductions of 1%-11%.

Under continuous-stage drought stress, yield reduction increased with drought intensity and duration. When replacing precipitation for two or more consecutive stages, yield reduction rates ranged from 2%-25%. When replacing precipitation for the entire growth period, yield reduction could reach 55%-75% under high-intensity stress. As water stress duration increased, severe yield losses or even total crop failure occurred.

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3 Discussion

Drought stress inhibits potato physiological and biochemical processes, causing yield and quality losses. The extent of loss is directly related to cultivar, drought stage, duration, and intensity. Leaf area index reflects potato photosynthetic characteristics and growth status, influencing multiple physiological and biochemical processes. Research by Wang et al. suggests that potato LAI is significantly positively correlated with drought resistance, consistent with our findings that LAI decreases with increasing drought intensity and duration. When potato experiences brief drought stress at the seedling stage, LAI is less affected, but stress during tuber formation and expansion stages elicits greater LAI response. Under drought stress, water deficiency causes stomatal closure, reducing transpiration and net photosynthetic rate, hindering potato growth. Water stress also inhibits cell growth, limits leaf expansion, and accelerates leaf senescence or abscission, severely affecting overall photosynthesis and consequently reducing LAI.

Potato aboveground (stems, leaves) and underground (roots, tubers) parts are closely related, exhibiting both interdependence and competition. Under short-term drought stress, the underground part may not experience water deficit and can grow normally, while the aboveground part suffers water deficiency due to stem/leaf elongation and transpiration, limiting aboveground growth and reducing biomass. In this study, aboveground biomass followed a logistic growth pattern: slow initial growth, accelerated growth after reaching a certain period, and slowed growth in later stages, consistent with findings by Qin (2013) on potato biomass under different irrigation regimes.

Drought stress during tuber formation reduces potato stolon number, thereby decreasing tuber number and final yield. Tuber expansion stage drought stress inhibits photosynthesis, reducing tuber number and yield, consistent with our finding that final yield is most responsive to branching-flowering stage water stress. In another study, potato plants adapted to mild drought stress showed less yield loss in subsequent drought events. Our study found that appropriate drought stress at the seedling stage increased final yield. In the model, dry matter accumulation rate is controlled by daily total solar radiation, water stress factor, temperature stress factor, and CO_2 concentration stress factor. According to our drought scenarios, reducing precipitation within a certain range does not significantly change soil moisture; but after prolonged water deficit when soil becomes very dry, plant potential transpiration decreases, the water stress factor reduces, and model dry matter accumulation rate consequently declines, reducing final yield. Additionally, when water is moderately reduced early in the growth period, dry matter translocation and partitioning to different organs changes accordingly. Within certain limits, reduced water increases the allocation proportion to potato roots, potentially improving final yield. Therefore, “seedling hardening” is commonly used in agricultural production to improve potato drought resistance and increase final yield.

In this study, potato yield decreased with increasing drought stress duration and intensity, except at the seedling stage. This occurs because drought stress inhibits overall plant growth, slows cell growth rate, suppresses photosynthesis, reduces plant height and aboveground biomass, ultimately decreasing potato yield. This pattern applies not only to potato but also to other crops. Studies have found that under drought stress, corn shows varying degrees of decline in ear length, plant height, and 100-grain weight. Winter wheat experiences no effect on photosynthesis or final yield under short-term mild water deficit, but as stress duration and intensity increase, water deficiency reduces photosynthesis, prevents adequate grain filling, and ultimately causes yield reduction. Therefore, timely irrigation is necessary during prolonged drought in potato production to ensure final yield.

Drought events frequently occur in China’ s potato production, limiting industrial development. Under current growth conditions, improving potato productivity is crucial for meeting national nutritional requirements. Clarifying water stress impact mechanisms and potato drought responses is essential for selecting drought-adapted varieties and developing field management measures. These theoretical foundations help maintain or even increase potato yield under climate change. Our study indicates that drought stress duration, intensity, timing, cultivar, and regional climate all affect potato growth and final yield.

However, several limitations exist: First, the APSIM-Potato model requires adjustment and determination of numerous parameters, and data from growth stages, aboveground biomass, and yield alone cannot meet all parameter adjustment needs. Second, our drought scenario design was relatively simple, only proportionally allocating precipitation by growth stage based on the baseline year, without considering extreme water conditions within a single stage. Additionally, the simulated environment differed from actual growing conditions, as factors like pests, diseases, and extreme weather were not considered. Future research should incorporate these environmental factors and obtain higher-precision field measurement data to better combine with field experiments and improve model simulation performance.

4 Conclusions

This study used daily meteorological data (1986–2020), soil data, and crop data from Wuchuan to evaluate APSIM-Potato model applicability. Based on local climate conditions, drought scenarios were designed and the validated model was used to simulate potato LAI, aboveground biomass, and yield responses to water stress at different developmental stages. The following conclusions were drawn:

(1) The APSIM-Potato model satisfactorily simulated potato growth and yield formation across different years in Wuchuan. The RMSE for growth stage simulation was within 3 days, with D-index above 0.85. The NRMSE for LAI, aboveground biomass, and yield simulation was below 20%, with R^2 and D-index above 0.85, demonstrating high simulation accuracy and model applicability in the study region.

(2) Under single-stage water stress, potato LAI, aboveground biomass, and yield decreased with increasing drought stress duration and intensity, though moderate water deficit during sowing-emergence increased yield. The branching-flowering stage showed the greatest response, with LAI, aboveground biomass, and yield decreasing by 3%-33%, 17%-35%, and 2%-25%, respectively.

(3) Under continuous-stage water stress, potato LAI, aboveground biomass, and yield decreased with increasing drought stress duration and intensity, with impacts showing continuity and cumulative effects. The entire growth period showed the greatest response, reducing LAI, aboveground biomass, and yield by 10%-57%, 29%-69%, and 55%-75%, respectively, while delaying the time to reach maximum LAI and aboveground biomass by 10–17 days and 13–18 days, respectively.

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Note: Figure translations are in progress. See original paper for figures.