

Analyzing Environmental Influences on Corn Yield: A Data-Driven Study in Champaign, Illinois

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Abstract

Project proposal

Crop models are computational tools that assess the effects of environmental variation and cultivation strategies on crop yield (Chapagain et al., 2022; Huang et al., 2019). By incorporating factors such as precipitation, humidity, temperature, fertilization, and soil properties, crop models establish relationships between input parameters and agricultural yield outcomes. From a structural perspective, crop models can be either empirical or mechanistic. Empirical models create statistical relationships based on existing data, while mechanistic models aim to explain relationships by exploring physiological mechanisms and causal connections (Reynolds and Acock, 1985). From a parameter standpoint, crop models generally include weather, soil, and crop-specific parameters to estimate crop biomass. Weather parameters cover solar radiation, precipitation, temperature, and more, while soil parameters focus on humus content, organic matter content, and other soil characteristics. Crop-specific parameters include maximum crop yield, specific nitrogen uptake rate, and related factors. In this project, we aim to replicate Hartmut Bossel's 'Field Crop Cultivation' simulation model as a white-box reference and develop a black-box model using SVD, PCA, and/or Fourier series. The original model is a parsimonious one, primarily focusing on the dynamic effects of precipitation on crop yield across a spectrum of crops in Germany. Initially created in BASIC (Hartmut, 1985) and later in Vensim (Hartmut, 2007) for educational purposes, the model simulates the impact of water and nutrient (nitrogen) availability on plant growth dynamics. Built from first principles, it captures complex interactions between water and nutrient dynamics and can be adapted to different scenarios by applying specific plant and soil parameters.

Data description

The dataset we plan to use is the meteorological records of Champaign, Illinois. We want to predict corn yield by analyzing precipitation and temperature. Data will be obtained from wunderground.com (Savoy, IL Weather History | Weather Underground). And daily temperature and the annual precipitation amount would be needed. The format would be primarily in CSV. The four columns will be temperature (including max, avg and min) and precipitation every day, while the rows will be the date for a whole year.

Exploratory data analysis

1. Background and Research Proposal Crop models are computational tools that assess the effects of environmental variation and cultivation strategies on crop yield (Chapagain et al., 2022; Huang et al., 2019). By incorporating factors such as precipitation, humidity, temperature, fertilization, and soil properties, crop models establish relationships between input parameters and agricultural yield outcomes. From a structural perspective, crop models can be either empirical or mechanistic. Empirical models create statistical relationships based on existing data, while mechanistic models aim to explain relationships by exploring physiological mechanisms and causal connections (Reynolds and Acock, 1985). From a parameter standpoint, crop models generally include weather, soil, and crop-specific parameters to estimate crop biomass. Weather parameters cover solar radiation, precipitation, temperature, and more, while soil parameters focus on humus content, organic matter content, and other soil characteristics. Crop-specific parameters include maximum crop yield, specific nitrogen uptake rate, and related factors.

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2. Reference model Construction In our project, we have already translated the model into Python as the reference model. We modularized the code into three phases to enhance customization and improve understanding: The first part of the code focuses on preparing input values, which involve defining constants and table functions that are used in the next stage. The second part integrates two sub-models: soil-water and soil-nutrient. The 'Soilwater' model determines the soil water content based on two key factors: water-related parameters and soil parameters. The water-related parameters describe the mass balance of water (precipitation, irrigation, transpiration, evaporation, and percolation). In parallel, the soil parameters define the water-holding capacity of the soil. The other sub-model 'Soilnutrient' contains a mass balance for nitrogen (the interconnection between plant available nitrogen and humus in soil). In summary, soil-water and soil-nutrient are fundamentally important to estimate the yield. In the third part, the output data is presented as diagrams (or in csv files), visualizing the simulation results and enabling analysis of how changing factors influence crop yield.

3. Data Preparation

3.1 Selecting Climate Zone and Sampling Points

United States: Corn Production



United States: Wheat Production



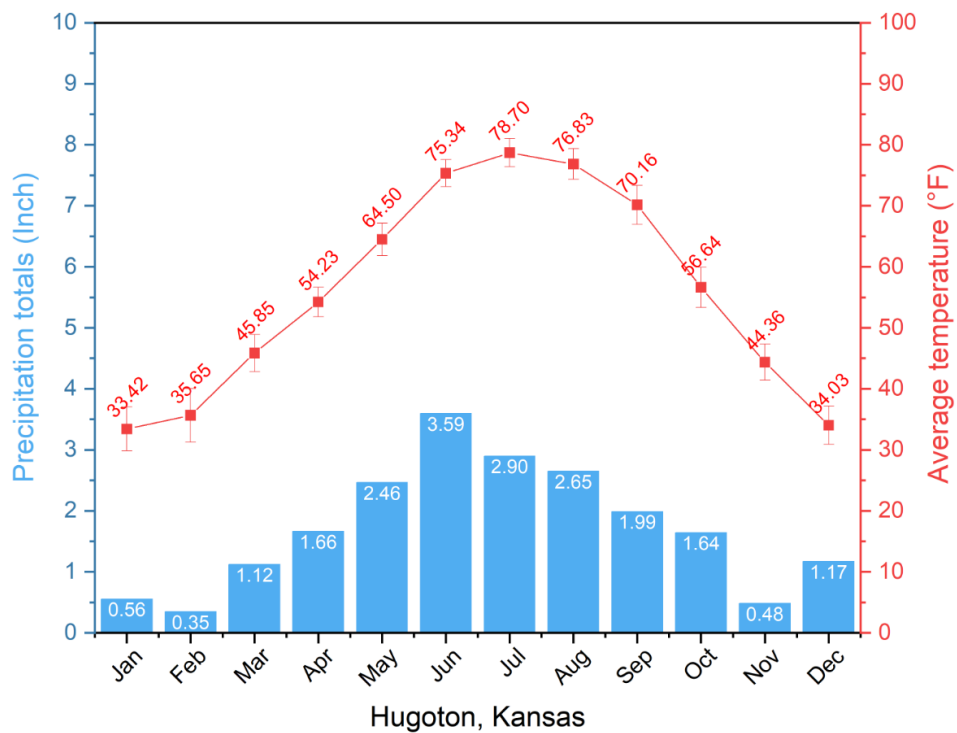
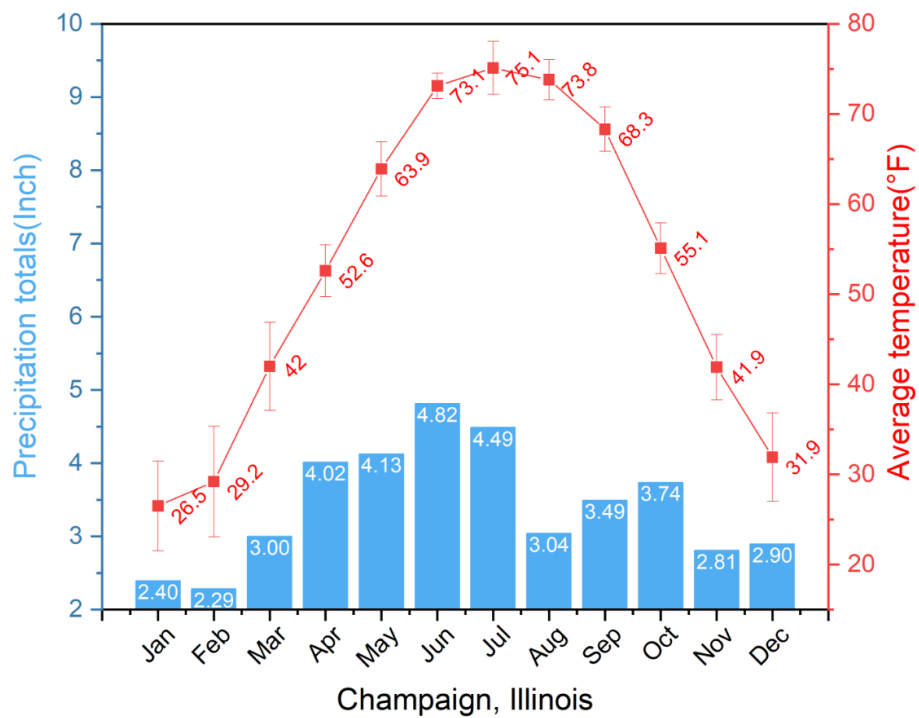
United States: Cotton Production



The figures above show an overlay analysis of the distribution percentages of corn, wheat, and cotton yields in the United States with climate zones. Our team determined the range of temperature and precipitation data needed by examining these overlays.

We can clearly see the locations where each crop's high-yield regions intersect with various climate zones, enabling us to understand how climate factors influence each crop's growth conditions.

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In this study, three typical U.S. crops, corn, cotton, and wheat, were selected as examples in our analysis. These crops are grown in different climate zones and play a vital role in U.S. agriculture. To scientifically analyze the impact of climate on crop yields, the study first chose climate data sampling points based on the United States crop production maps (USDA United States - Crop Production Maps), which clearly shows the key production areas for different crops. Climate data, including monthly average temperature and monthly precipitation, were collected from three different weather monitoring stations within each key production area. Climate data from 2004 to 2024, within a 20-year period of time, were collected and used in this study for model analysis.

Here, we chose to represent the climatic characteristics of a region using the monthly average temperature and monthly average precipitation for each year. For example, the State of Illinois, of which mostly is humid continental climate, is a major corn production area in the US. The characteristics of this climate type is presented by temperature and precipitation data from Champaign. Similarly, we chose Nobel County in Minnesota as a typical wheat-producing area to illustrate its climate characteristics, and Port Mansfield in Texas to represent the climate characteristics of a typical cotton-growing area.

4. Reference Model Results Analysis and Questions

4.1 Exploratory Data Analysis on Reference Model Results, Humid Subtropical Climate



Figure 1. Model Results Under Varying Precipitation in Humid Subtropical Climate (Stoneville, MS)

Figure 1. shows the mechanistic model results for soil water and nutrient dynamics in a humid subtropical climate (Stoneville, Mississippi) under varying precipitation scenarios (maximum, mean, and minimum). The results are shown in two sets of plots. The x-axis represents time within one year, ranging from 0 to 1. Plots in the first row (a, b, c) display the changes in soil nutrients over time, specifically total biomass (red), nitrogen available to plants (green), and organic matter fraction in soil (blue). Plots in the second row (d, e, f) illustrate the in precipitation with randomized weather event (blue line), groundwater levels (red line), and soil water content (blue line) across three precipitation scenarios.

From the soil nutrient data, we can observe the seasonal dynamics of biomass levels as well as plant-available nitrogen in the soil. At the beginning of cultivation, with the application of fertilizer, nitrogen levels reach their peak and then decrease as the crop continues to grow. From the soil water data, we can see that a water surplus exists in both the max and mean rainfall scenarios, leading to a significant rise in groundwater levels (d, e). Additionally, since the reference model did not account for surface runoff, there could be a significant overestimation of precipitation's contribution to groundwater levels.

4.2 Further Questions on Reference Model Results, Humid Subtropical Climate

1. Model Glitch: Notice that, despite the differences in precipitation levels, plots a, b, and c are largely identical. It appears that the sub-model 'Soilwater' is not successfully linked with the other sub-model 'Soilwater' in the simulation. Further debugging is required to calibrate the reference model.
2. Optimal Precipitation for Corn Growth: Even under minimum precipitation, there is no significant water deficit; thus, all crops grow under optimal water conditions. However, how does each scenario impact actual corn yield in Stoneville? Can the model accurately reflect the optimal precipitation range for maximum crop growth?
3. Nutrient Leaching: Will excessive rainfall affect nutrient level through leaching and erosion? The original model was designed to represent moderate conditions at or below optimal precipitation, but could high precipitation levels cause additional nutrient loss in other pathways?
4. Model Validation: How well do these model outputs align with real crop yield data from similar climate zones? (This may exceed the scope of our project.)
5. Long-Term Soil Health Under Crop Rotation: Over multiple growth cycles and by applying sustainable practice such as crop rotation, what would be the cumulative effect in the long-term on soil nutrient content and water content? (Exceeding the scope.)

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Figure 2. Model Results Under Varying Precipitation in Humid Continental (warm summer) (Arnold, IA)

Figure 2. shows the mechanistic model results for soil water and nutrient dynamics in a humid subtropical climate (Arnold, Iowa) under varying precipitation scenarios (maximum, mean, and minimum). The similarity of soil nutrient results is probably caused by model error. In soil water, we can see three precipitation cases cover highwater excess, minor water deficit and large water deficit, indicating that the locational conditions can be a good setting for us to use this reference model to explain the situation. Also, notice that the precipitation pattern (blue) is different from Stoneville, and hence causing different dynamics in soil water content (green), for example, not significant seasonal variation.

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- Model Glitch:** Given that precipitation in this scenario is below the optimum level, it can be confirmed that there is a model glitch. In the original model, when water availability is below optimal, both crop growth and microbial activities (which affect the transformation of organic matter into plant-available nitrogen) in the soil should be reduced. Therefore, the overall biomass curve should shrink vertically (red), the available nitrogen level should remain low instead of increasing (green) after harvesting, and the organic matter level should remain high (blue) after harvesting.
- Dataset Scope:** In the future, we may limit our climate zones to Humid Continental or drier regions to avoid the structural limitations of the mechanistic model in explaining crop yield under heavy rainfall conditions and accounting for surface runoff in the region's water balance.
- Evapotranspiration (ET) Rate Correction:** Currently, the reference model characterizes the ET rate as a constant. Since we are using this model in different locations with varying humidity, temperature, and wind speed, we could enhance the model's accuracy by incorporating location-specific ET rate.

5 Predictive Modeling Plan The aim of this project is to create a statistical model to produce similar estimates as the mechanistic model. The benefit of this simplification is to reduce computational costs. Another potential outcome of this approach is that, by using regression analysis, we can test correlations and rank the inputs that have the most significant effect on the output, thereby helping to determine the dominant factors influencing crop growth and decision-making in crop management. To do this, we will first ensure that the reference mechanistic model functions correctly, making it capable of generating predictive yield based on the precipitation data. Then, to create sufficient data, we can randomly generate 1,000 (or more) precipitation curves for each scenario using the mean value and standard deviation obtained from the data in section 3. Third, the generated precipitation curves will be stored as CSV files, ready for model input. Fourth, we will translate the current Python model into Julia and automatically run simulations to obtain the corresponding yield for each precipitation scenario. Finally, we will compile a new DataFrame that includes both the precipitation

and yield data, allowing us to apply SVD, PCA, and/or Fourier series to identify the dominant eigenvectors and underlying patterns in the data.

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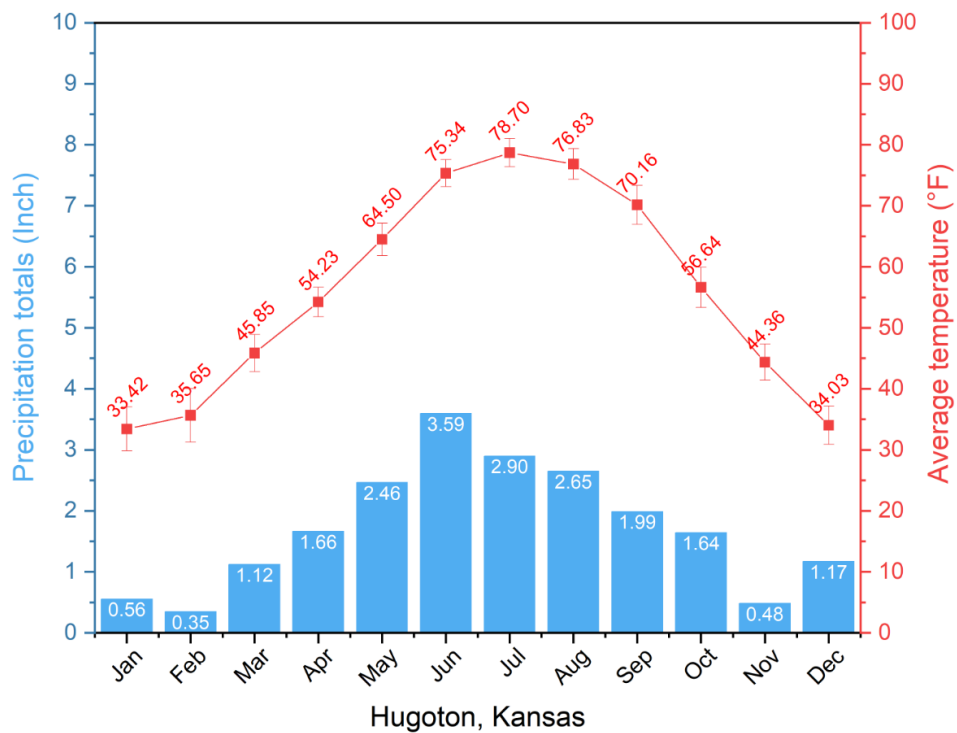
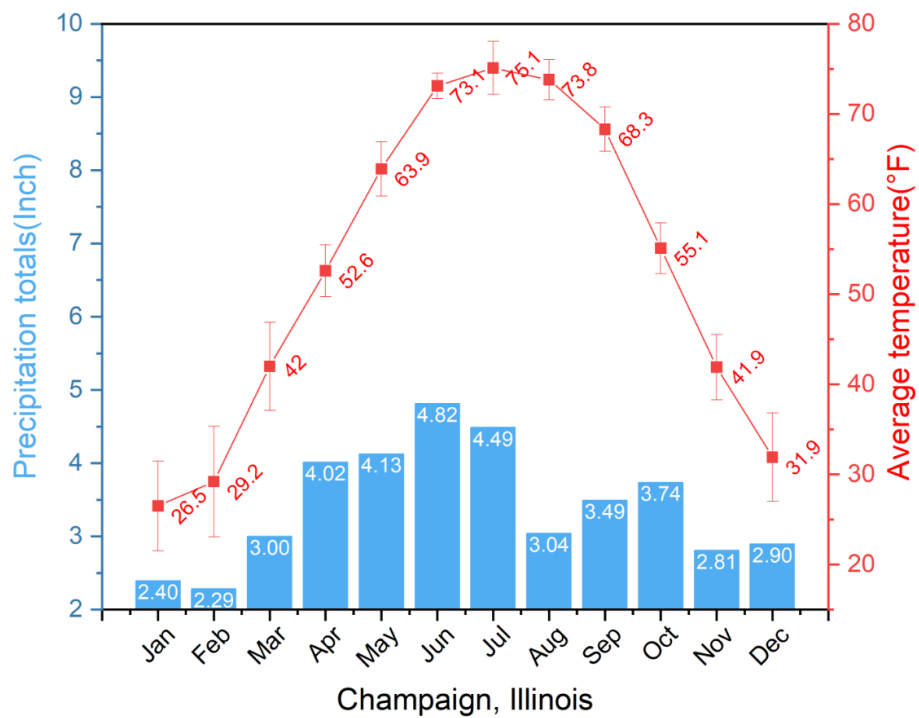
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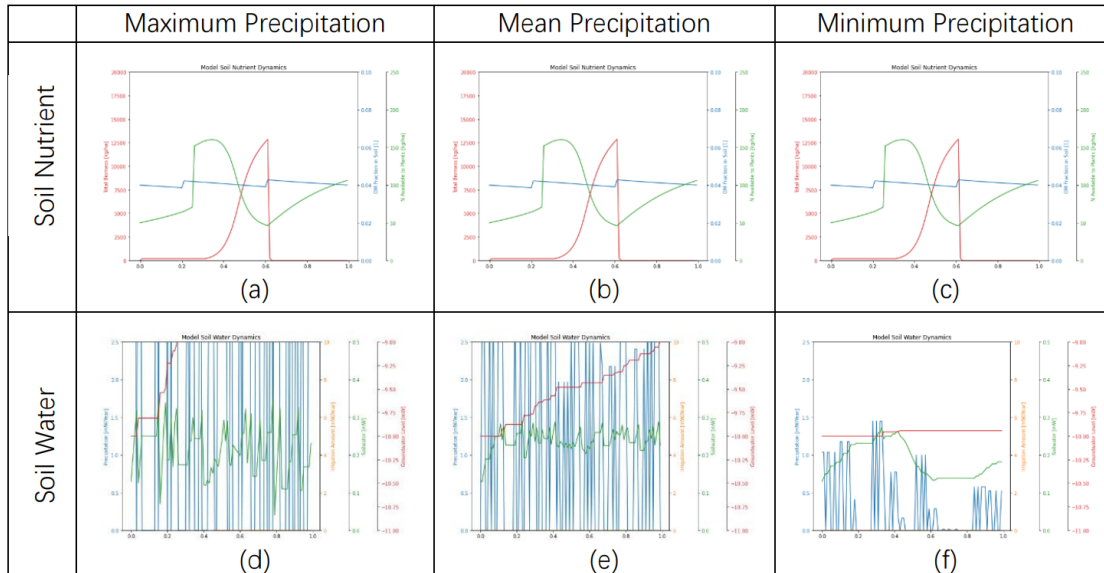


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and yield data, allowing us to apply SVD, PCA, and/or Fourier series to identify the dominant eigenvectors and underlying patterns in the data.

Preliminary predictive modeling

Data Description

Explanation of Columns

The dataset includes several key columns, each playing an essential role in the analysis. The *sim_index* column represents the simulation timeline, allowing the data to be tracked sequentially. While not directly used in the model, it helps visualize time-dependent trends. The *MULTIPLIER_FOR_RAINFALL* column is a scaling factor applied to raw rainfall data, reflecting environmental adjustments or experimental conditions. Using this multiplier, the *rain_amount* column is calculated as the cumulative rainfall over time, serving as the independent variable in the regression analysis to explore its impact on biomass production. The *precipitation* column indicates the level of rainfall at each time point, providing additional environmental context. Similarly, the *soil_moisture* column captures the moisture levels in the soil, influenced by rainfall and precipitation. This column is not directly used in the predictive model now. Finally, the *total_biomass* column represents the dependent variable, measuring the biomass produced under given conditions. This serves as the target variable in the regression model, with predictions based on the *rain_amount* variable. Together, these columns create a comprehensive dataset for analyzing the interplay between rainfall and biomass in varying environmental conditions.

Relationships and Usage in Code

The dataset's variables are used in specific ways to build and analyze the predictive model. The *rain_amount* column, derived by multiplying *MULTIPLIER_FOR_RAINFALL* and *raw rainfall* data, serves as the core predictor to model its relationship with *total_biomass*. This dependent variable acts as the target for the regression analysis, allowing the model to evaluate its predictive accuracy. Supporting variables such as *precipitation* and *soil_moisture* provide additional environmental context, which could be leveraged for feature engineering in more advanced models. The *sim_index* ensures that the data can be tracked sequentially for exploratory analysis and visualization. These relationships enable the construction of a decision tree regression model, which uses *rain_amount* to predict *total_biomass*, and its performance is validated through visualizations and comparisons with the observed data.

1 Model Construction and Analysis

1.1 Decision Tree Regression

For this project, we implemented a custom decision tree regression model. Below is the detailed logic of the model: Model Principle: The decision tree recursively partitions the data, dividing the feature space into smaller subregions. Each subregion is represented by the mean value of the target variable. The tree-building process involves: Optimal Split Selection: Iterating through all possible split points (unique rainfall values) to minimize the Mean Squared Error (MSE). Recursive Subtree Construction: Splitting data into left and right branches and continuing until the predefined maximum depth or a minimum number of samples is reached. Termination Criteria: If the sample size in a node

is less than `min_samples_split` or the tree reaches the maximum depth, the node returns the mean value of the target variable.

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