Problem Chosen	2023	Team Control Number
A	MCM/ICM Summary Sheet	2314370

Decode the Interactions in Plant Communities

Summary

Drought is an inevitable disaster that exists in various environments. Its cumulative, not obvious impact severely affects the plant community. Coping with drought, plants evolve various complex strategies. The insurance strategy and numerous observations are suggesting that the diversity of species plays a role in how a plant community adapts in drought. In order to shed insights into how a plant community benefits from biodiversity and how it survive in drought, we propose the **PGPC** (Prediction for the Growth of a Plant Community) model to explore the philosophy behind biodiversity and adaptability of a plant community.

Firstly, the **PGPC** model is based on **ecological dynamics**. To predict how plant communities change in drought, we derive a non-linear equations system, each of which represents a factor affecting plant growth. With climate and bioclimate condition, it allows us to dynamically calculate the biomass of all individual species in the community.

Specifically, in order to simulate the growth of plant communities in their natural state, we consider not only the factors of **plants themselves (e.g., phothsynthesis and transpiration)**, but also **abiotic factors (e.g., precipitation, light intensity, Temperature)** and the **interactions (e.g., symbiotic and antisymbiotic)** between different plant species. **Water Use Efficiency** of the whole plant community is the key in this paper to solve the interactions. Overall, when a plant community is exposed to various irregular weather cycles, communities with the **optimum combination of plant species** survive **20%** longer than communities with other species and accumulate **25%** more biomass over a given period.

Next, to explore the **resistance of our optimum combination of species** to different levels of drought, we conducted **controlled trial** in computer simulation. The results showed that both high frequency and long duration of drought reduced the survival time and biomass of the community. Also, **the proposed optimum combination of types of plants to adapt to drought is valid regardless of the level of drought**.

Last, to test the sensitivity of the model, disturbance factors like **environment pollution** and **habitat reduction** are added. Environment pollution contaminates the quality of water, thus reducing the growth of plants, and the reduction of habitat lowers space resources, thus decreasing the effective photosynthesis of plants. After simulation, **the survival time and total biomass of the plant communities associated with any one of these two factors decreased**.

In summary, to ensure the long-term viability of a plant community, the proposed optimum combination of species is worth of highly recommendation.

Key words: Ecological Dynamics, The Insurance Hypothesis, Drought Adaptability, Nonlinear ODEs, PGPC.

Contents

1 Introduction

1.1 Problem Background

Plants are exposed to various environmental stresses during growth and development under natural conditions. Among these, drought is one of the most severe environmental stresses affecting plant productivity. Cope with drought, plants evolve various complex resistance and adaptation mechanisms to survival. According to a large number of observations, populations with more plant species show better adaptability and resistance in drought extremes. These observations inspire us to explore how a plant react to drought and how different species interact with each other.

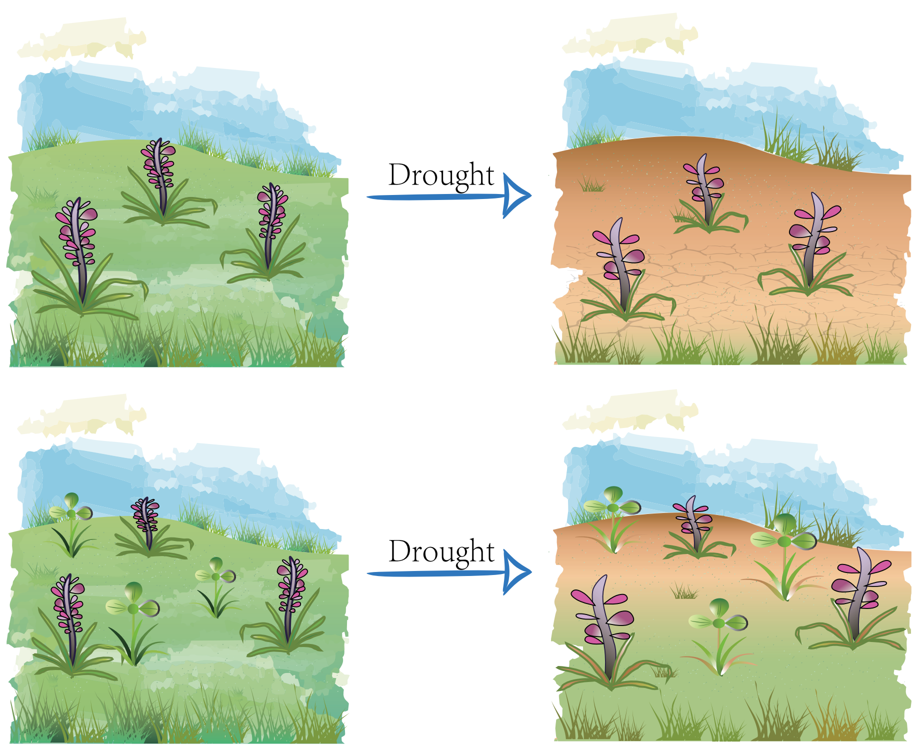


Figure 1: The impact of drought on different plant communities composed of different species. The species of the plant community in the two sub-figures below is more diverse than the plant community in the two sub-figures above.

1.2 Literature Review

Since the last century, the insurance hypothesis[1] has been the focus of scholars in related fields. They have carried out a large number of experiments and researches to test the hypothesis that larger numbers of species should enhance ecosystem reliability.

According to the diversity insurance hypothesis, an increase in community diversity corresponds to an increase in the range of potential species responses to environmental perturbation. That is, communities with larger numbers of species and more diverse have a better resistance in drought and the more-adapted species can compensate for the biomass loss of less-adapted species. Several drought experiments have been carried out to test the diversity insurance hypothesis. The presence of drought-resistant species increases plant community insurance against drought and, hence, is important for the functioning of grassland ecosystems[2]. Therefore, the interactions between the less-adapted species and more-adapted species might act as a key factor in enhancing community adaptability to drought.

Various plants react to drought in different ways [3]. One of the main strategies is to improve water-use efficiency (WUE) under conditions of water deficiency. In fact, higher WUE indicates a higher biomass production. Different species interact with each other through underground root, improving the overall plant community WUE. Long-rooted plants can absorb water from deep soils, even groundwater, and draw water to shallow soils through transpiration, so that short-rooted plants can absorb more water. Phytohormones can also be released by phytohormones-releasing plants, thus promoting the growth of roots of short-rooted plants, which can draw water from the deeper soil layers[4].

Thibault Moulin *et al* develop a dynamic, process-based ecological model named $DynaGraM$ to simulate the competition and adaptation processes in community dynamics[5][6]. The total biomass of the plant community is projected under given soil and climatic conditions. However, it does not take into account the interactions between different species of plants.

Inspired by the insurance hypothesis and $DynaGraM$ model, we hope to provide a new solution to uncover the interaction between different species in a plant community and how it enhance the adaptability in drought.

1.3 Problem Restatement

Here, we list out the aspects of the problem that we aim to address along with the section(s) in this paper where they are discussed:

- How different plant communities composed of different species respond and how they change during irregular weather cycles? (Methods in Section 4.5; Results in section 5.1)
- What is the impact of types of species on community and optimum combination of plant

species in drought. (Section 5.2, 5.3)

- How the frequency and duration of drought affect the biomass of the plant community. (Section 6)
- How environmental pollution and reduction of plant habitats affect the plant community.(Section 7)
- Considering the natural and human factors, we propose feasible strategies to ensure the long-term viability of a community and find out what are the impacts on the larger environment. (Section 8)

1.4 Our Works

In this paper, our objective is to develop a mathematical model to predict how a plant community changes over time as it is exposed to irregular weather conditions. Based on this model, we attempt to have in-depth understanding of the impact of different levels of drought, natural and human factors and interaction between species to ensure the long-term viability of plant populations.

In order to avoid complicated description, we draw the flow chart to reflect out work process intuitively, which is shown in Figure 2 :

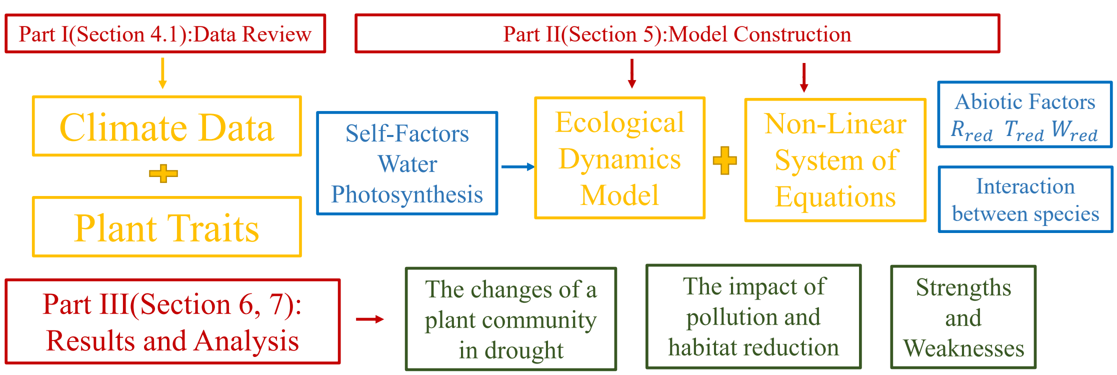


Figure 2: Framework of this paper

2 Assumptions and Justifications

- **Assumption 1:** We only consider the plant community in the grassland.
  Justification: Plant communities on grasslands are more sensitive to changes in drought conditions, so the data and results are more reflective of the relationship.

- **Assumption 2:** The climate data in in steppe of stavro is utilized to as the baseline to generate various irregular weather conditions.
  Justification: Steppe of stavropol is a typical temperate drought grassland in Russia, with annually only $200 \sim 300\ mm$ precipitation, which is appropriate for the simulation of drought of grassland.

- **Assumption 3:** If plants do not absorb water from the soil for 7 days, they die.
  Justification: Water is an important element in plant metabolism, and the lack of water will make it impossible for plants to carry out respiration and photosynthesis.

- **Assumption 4:** The growth state of plants is measured by the biomass of plants.
  Justification: Changes in plant biomass are related to respiration and photosynthesis, so they can reflect the state of plant growth to a certain extent.

- **Assumption 5:** Use discrete data to calculate changes in plants。
  Justification: On a daily basis, the change of plants is slow, thus we can use discrete data to approximate the continuous change process of plants.

- **Assumption 6:** Only mutually beneficial symbiotic relationship between plants is considered.
  Justification: There is competition in plant-to-plant relationships, but in mild drought conditions, mutually beneficial symbiosis dominates inter-plant relationships.

- **Assumption 7:** Only moisture and light are considered in plant growth factors.
  Justification: The amount of nitrogen in the soil and the action of microorganisms also affect plant growth. However, in drought conditions, nitrogen and microorganisms did not change, which could not reflect the relationship between plant communities and drought.

- **Assumption 8:** Grassland plants are categorized into three types according to their traits.
  Justification: Under drought conditions, we mainly focus on water resources, so in order to show the relationship more intuitively between plant community and drought, several specific traits are selected to categorize.

Other assumptions are given and justified in the relevant content.

3 Nomenclature

Here are all the variables, parameters and abbreviations in this paper.

Variable	Meaning
B	Biomass
WR	Water Reserve in Shallow Soil
GW	Ground Water
Parameter	**Meaning**
$\bar{P}$	Annually Precipitation
T_s	Average Temperature in sunny days
T_r	Average Temperature in rainy days
T_d	Average Temperature in drought days
μ	leaf senescence rate
T_m	Optimum Temperature for Photosynthesis
RUE_{max}	Maximum Radiation Use Efficiency
α	Empirical constant for Photosynthesis
η	Empirical Constant for Water Circulation
κ	Empirical Constant for Water Absorption
Abbreviation	**Full Name**
$PGPC$	Prediction for the Growth of a Plant Community
PET	Potential Evapotranspiration
PAR	Photosynthetically Active Radiation
SLA	Specific Leaf Area
LAI	Leaf Area Index of the Canopy
LAM	Percentage of Laminae Present in the Green Biomass
WUE	Water Use Efficiency

4 A Comprehensive Model: Prediction for the Growth of a Plant Community (PGPC)

The growth of a plant community is determined by various factors, such as self-factors, abiotic factors and interaction between different species. Therefore, we use ecological dynamics model which consists of a non-linear equation system of n+2 ordinary different equations. Each equation represents a factor that determines the growth of a plant community. Based on the values of different factors for each day, we can dynamically calculate the changes in the plant community. Thus, the prediction based on PGPC model is a good approximation and reasonable.

4.1 Data Overview

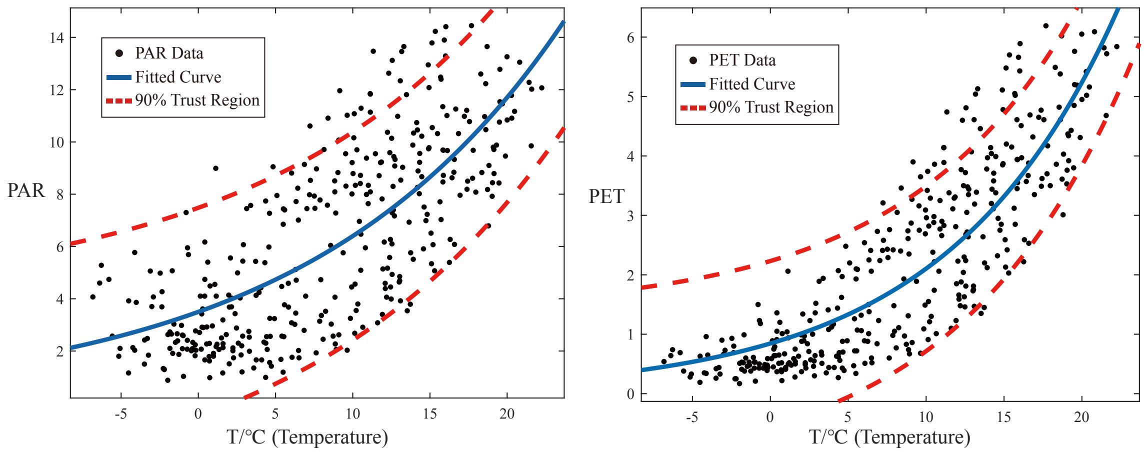
The sources of the data used in this paper are listed in Table 1. The climate data related to the temperature and precipitation is collected in steppe of stavropol, which are summarized in Table 2. Steppe of stavropol is a typical temperate drought grassland in Russia, exactly $45.05°$ and $41.97°$ in latitude and longitude respectively, with annually only $200 \sim 300\ mm$ precipitation. Hence, the climate data in steppe of stavropol is utilized to simulate the weather condition in drought. The bioclimate data in [5] is used to fit the relationships of potential evapotranspiration (PET) and photosynthetically active radiation (PAR) versus temperature, both of which are highly temperature dependent, and the fitting results are shown in Figure 3. The traits of the plants considered in this paper are given in Figure 4 and Table 3. All the parameters listed will be discussed in detail in the following.

Relevant Data	Data Source
Climate	WorldClim[7]
Bioclimate	Thibault Moulin *et al*[5]
Plant Traits	Plant Science Data Center

Table 1: Data Sources

Climate data	$\bar{P}$	T_s	T_r	T_d
steppe of stavropol	$3\ mm/d$	14 °C	8 °C	20 °C
standard deviation σ	$\pm 1\ mm/d$	$\pm$ 1 °C	$\pm$ 1 °C	$\pm$ 2 °C

Table 2: Climate data in steppe of stavropol



(a) PAR versus T (b) PET versus T

Figure 3: Fitted relationship of (a) $PAT\ vs\ T$, (b) $PET\ vs\ T$

(a) Short-Rooted Plant (b) Long Root-Rooted Plant (c) Phytohomones-Releasing Plant

Figure 4: Plants categorized by mutual interaction

Traits	Example	Root Length	SLA	μ	T_m
Short-Rooted	Poa trivialis	$10 \sim 20\ cm$	0.0331	0.0250	8.0
	Nardus stricta	$10 \sim 30\ cm$	0.0110	0.0115	15.0
	Trisetum flavescens	$10 \sim 40\ cm$	0.0205	0.0212	14.0
Long-Rooted	Bromopsis erecta	$1 \sim 2\ m$	0.0155	0.0160	15.3
	Lotus corniculatus	$\leq 1.5\ m$	0.0224	0.0173	11.5
	Trifolium pratense	$1 \sim 8\ m$	0.0228	0.0175	11.5
Phytohomones Releasing	Lolium perenne	$10 \sim 50\ cm$	0.0286	0.0303	7.5
	Heracleum sphondylium	$20 \sim 40\ cm$	0.0230	0.0176	9.0
	Taraxacum officinale	$10 \sim 30\ cm$	0.3240	0.0224	12.5

Table 3: Traits of plants in this paper

4.2 Sub-model 1: The Growth of a Plant Community

At the macro level, plant communities contain a wide variety of plant species. It is challenging to directly analyze the changes in the whole plant community. Therefore, we predict the overall trends of plant communities by calculating the changes of all individual species in the community.

For the whole plant community and individual species, biomass is introduced to measure the growth change. For a given species i, green biomass dynamics is described in equation 1

$$\frac{d}{dt}B_i(t) = Gr_i[B_i(t), PAR(t)] - \mu_i\, SEN(t) \tag{1}$$

where Gr_i expresses potential growth as a function of biomass B_i and PAR, both of which are time-dependent. This potential growth Gr_i corresponds to the maximal growth obtained in optimum conditions regarding water resources and temperature. Equation2 describes the efficiency of use of solar radiation and competition for sunlight by different plant species. $\mu_i\, SEN(t)$ is the biomass of senescent leaves, because of metabolism.

$$Gr_i[B_i(t), PAR(t)] = 10PAR(t)RUE_{max}[1 - e^{-\alpha LAI_{tot}(t)}]\frac{LAI_i[B_i(t)]}{LAI_{tot}(t)} \tag{2}$$

$$LAI_i[B_i(t)] = \frac{1}{10}B_i(t)SLA_i\, LAM \tag{3}$$

$$LAI_{tot}(t) = \sum_{i=1}^{n} LAI_i[B_i(t)] \tag{4}$$

In the equation 3, LAI_i is the leaf area index of the canopy of species i and LAI_{tot} is the total leaf area index of the canopy. SLA_i is the specific leaf area of species i, 10 is a dimensionless number, LAM is the percentage of laminae present in the green biomass, RUE_{max} is the maximum radiation use efficiency of the whole canopy and α is the extinction coefficient which is a constant for all species.

4.3 Sub-model 2: Abiotic Impacts on the Growth of a Plant Community

Abiotic factors which have impacts on the growth of a plant community are modelled as the multiplication of several reducers as shown in equation 5.

$$\Gamma_i = R_{red}T_{red,i}W_{red} \tag{5}$$

The first term, R_{red}, is regraded with the reduction of RUE when the light intensity is beyond the optimum value, proposed by Schapendonk $et\ al$[8]. This value is set to be identical to all species since it's completely determined by daily PAR, which is a climate related data. The second reducer $T_{red,i}$ is introduced by daily temperature, which models the effect of environment temperature on photosynthesis. One thing should be noted that $T_{red,i}$ is species related, since different optimum temperatures for different species is considered in our model. The last term W_{red} is the reduction caused by water reserve, which is the most important in our model. It describes the factors mainly influencing the photosynthesis, including the amount of water available in shallow soils, the water stress on its root and etc[5]. This term varies slightly in species in the case of drought.

4.4 Sub-model 3: Interaction Impacts on the Growth of a Plant Community

In mild drought, water is the most critical factor in determining plant growth and soil has a certain water retention capacity. Plants draw water from shallow soil through their roots, and the daily precipitation replenishes the water lost in the soil due to evaporation. At the same time, groundwater is introduced, which is embedded in the deep soil and supplied by the penetration of daily precipitation. Most importantly, it plays a role in the network of roots of different plant species connected to each other through groundwater to interact. According to the interaction between different species and groundwater, we categorize common plants in grassland into three types,

- **Short-Rooted Plant**: typically with root shorten than $50\ cm$, which means that this type of plant cannot draw water from groundwater in drought.
- **Long-Rooted Plant**: typically with root longer than $1\ m$, so that this type of plant is capable of transporting groundwater in deep soil to shallow soil, which is beneficial to short-rooted Plants.
- **Phytohormones-Releasing Plant**: capable of releasing phytohormones, which can boost the growth of the root of short-rooted plants and make it possible for them to draw groundwater to survive.

The details of these three types of plants can be found in Table 3. Hence, as shown in Figure5(a), an overall water circulation exists throughout the system. Additionally, considering the capacity of water of shallow soil and deep soil, the loss of water is also modelled in the circulation. The circulation can be formulated as follows,

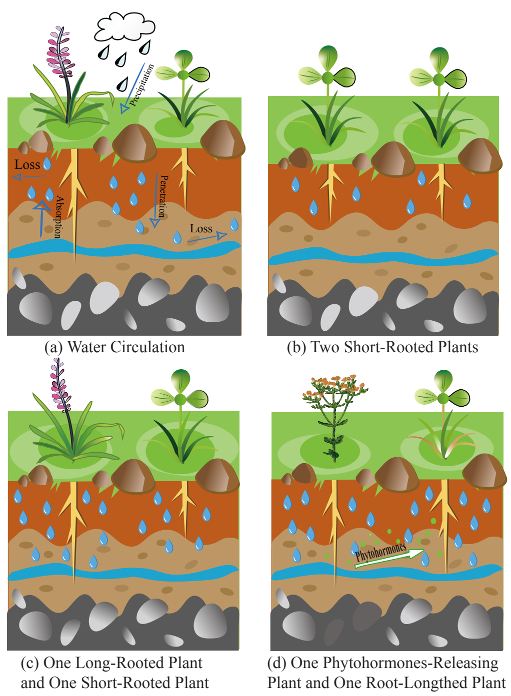
$$\frac{d}{dt}WR(t) = P(t) - AET[B_i(t), WR(t), PET(t)] \tag{6}$$

$$\frac{d}{dt}GW(t) = f[WR(t)] = \begin{cases} \eta\, WR(t) & if\ WR(t) > 0 \\ 0 & if\ WR(t) = 0 \end{cases} \tag{7}$$

where WR is the current volume of water in the shallow soil, P is the precipitation, AET is the consumption of water in the shallow soil by photosynthesis and circulation, η is an empirical parameter for the penetration rate and GW is the current volume of groundwater. If drought occurs, when the amount of water temporarily stored in the shallow soil is consumed to zero, the roots of different species of plants begin to draw water from groundwater, in Equation 8.

$$\Delta(t) = \begin{cases} 0 & if\ WR(t) > 0 \\ min(\frac{GW(t)}{\varepsilon}\frac{\sum_r B_r(t)}{\sum_{i=1}^{n} B_i(t)}, \kappa) & if\ WR(t) = 0 \end{cases} \tag{8}$$

where κ is an empirical parameter for the volume of water draw from the groundwater in one time, $\sum_r B_r(t)$ represents the total biomass of plants that can absorb groundwater and ε represents the duration of drought. The proportion of the biomass of plants that can absorb water and total plants is multiplied to model the effect of space occupation. Interactions of different species have great impacts on the water circulation, which inversely affect the growth of themselves. As shown in Figure 5, the water reserve in shallow soil is replenished in Figure 5(c) and 5(d) comparing to the water deficiency in Figure 5(b) due to interactions of different species of plants.



(a) Water Circulation

(b) Two Short-Rooted Plants

(c) One Long-Rooted Plant and One Short-Rooted Plant

(d) One Phytohormones-Releasing Plant and One Root-Longthed Plant

Figure 5: Water Circulation and Interactions Between Different types of species

4.5 Synthesis of Our Model

Three sub-models discussed previously comprises of our comprehensive model, which is synthesized in Equation 9. The ecological dynamics of a plant community can be described in this synthesis equation, which means that we can **predict the evolution of a given plant community under any weather cycle**. The discrete form and implementation of our synthesis model is given in Algorithm 1.

$$\begin{cases} \frac{d}{dt}B_i(t) = Gr_i[B_i(t), PAR(t)]\Gamma_i \\ \frac{d}{dt}WR(t) = P(t) - AET[B_i(t), WR(t), PET(t)] + \Delta(t) \\ \frac{d}{dt}GW(t) = f[WR(t)] \end{cases} \tag{9}$$

Algorithm 1: Prediction for the Succession of a Plant Community

Input: temperature array T, precipitation array P, Species Number n, Bioclimate array μ, SLA, T_m;

Output: biomass array B, soil water reservation array WR, ground water reservation array GW;

$i = 0$; % Species Index
Initialize $WR[0]$, $GW[0]$;
while $i < n$ **do**
  Initialize $B[0]$;
  $t = 0$; % Time in day
  while $t <$ *maxIteration* **do**
    $B[i][t+1] = B[i][t] + Gr(B[i][t], PAR[t]) * \Gamma[i][t] - \mu[i] * SEN(T[t])$;
    $WR[t+1] = WR[t] + P[t] - AET(B[i][t], WR[t], PET(t)) + \Delta(GW[t])$;
    $GW[t+1] = GW[t] + f(WR[t]) - \Delta(GW[t])$;
    $t = t + 1$;
  end
end
return B, WR, GW;

5 Preliminary Results and Analysis

Utilizing our PGPC model, we projected the changes in the plant community under various irregular weather cycles, taking into account interactions between different species. The climate data in steppe of stavropol is used as the baseline to generate one irregular weather cycle in a year and the simulation result of the growth of one mixed plant community is provided in *Section 5.1*. The impacts of interactions of different species on the growth of the plant community are explained and verified in *Section 5.2*. *Section 5.3* gives the optimum combination of different species to adapt to drought.

5.1 Simulation to Various Irregular Weather Cycles

Table 2 is set as the baseline to generate various irregular weather cycles. The studied time period is set as one year, with sunny days, rainy days and drought days are randomly allocated into this one year period. Additionally, several rainy days are allocated in each duration of drought days to consider extreme weather condition. The daily temperature and daily precipitation are recorded in Figure 6. In this task, one plant community includes all three types of plants we defined before, which means that there exists a complete water circulation in the environment of this community. The changes of the volume of WR and groundwater are plotted in Figure 7. **The interactions between different species are implied, where the groundwater is continuously drawn by the long-rooted plants and the root-lengthened plants to replenish the WR to feed their growth.** In figure 8, the biomass is continuously increasing regardless of drought days and sunny days, due to the collaboration of different species.

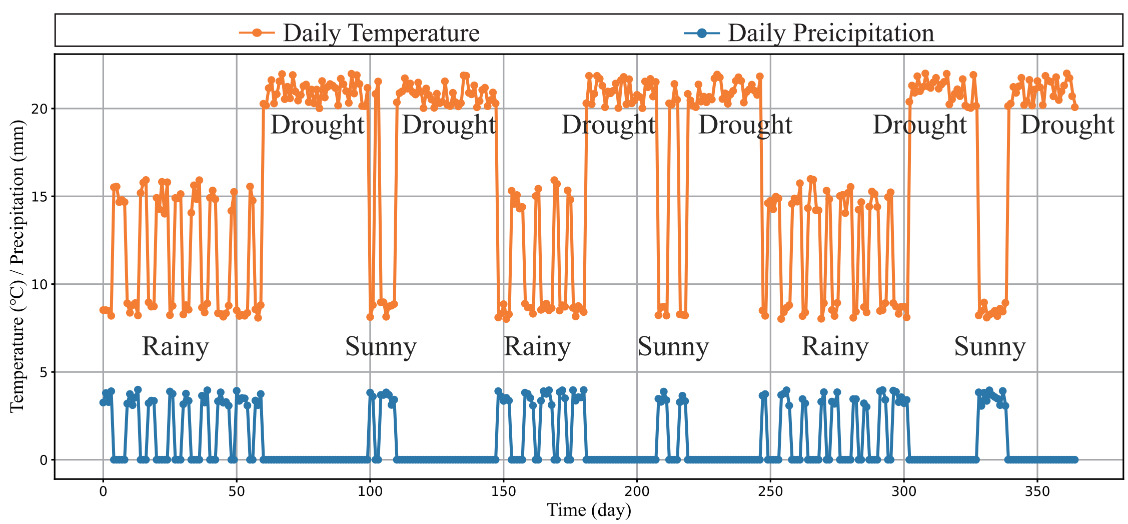


Figure 6: Daily temperature and daily Precipitation in irregular weather cycles

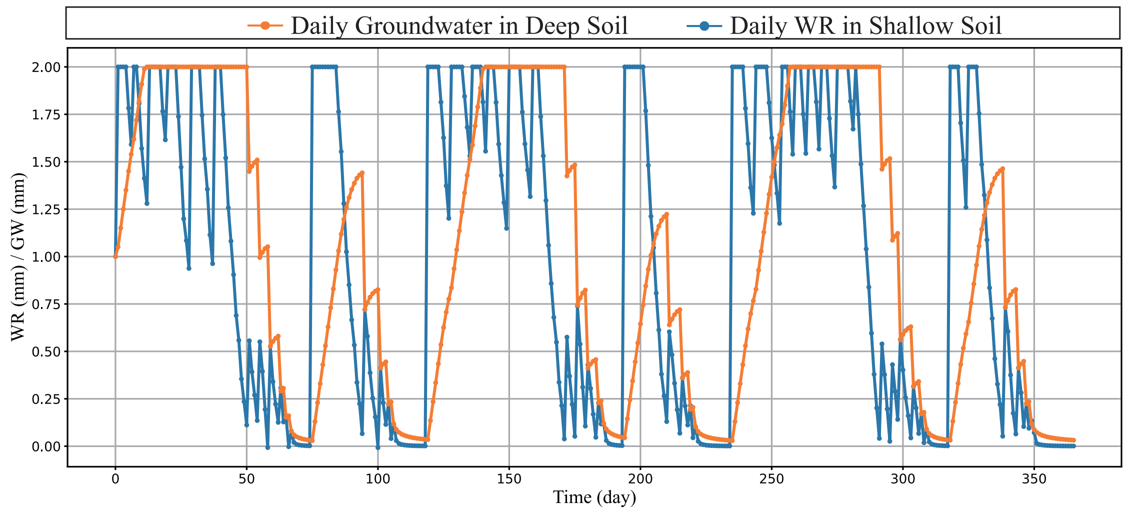


Figure 7: The volume of daily groundwater in deep soil and WR in shallow soil

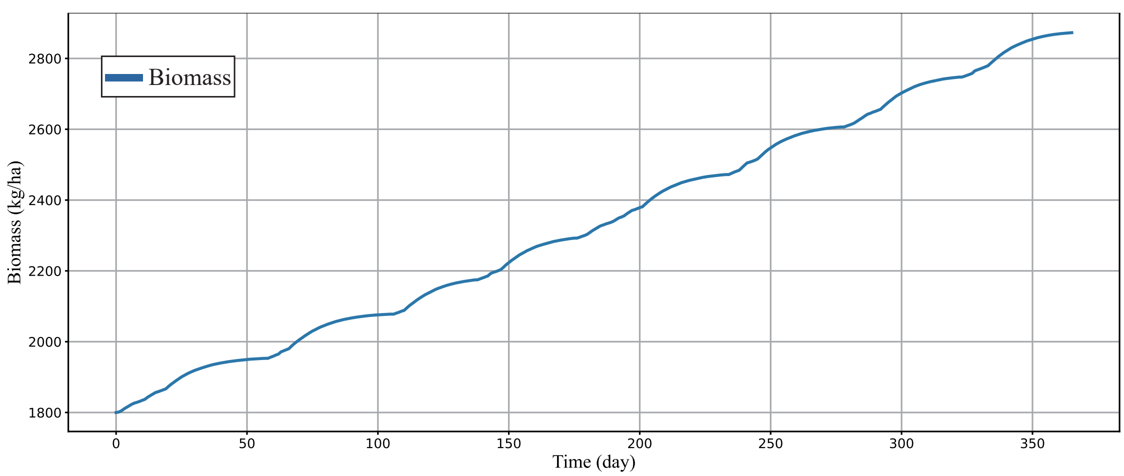


Figure 8: Growth of biomass in a year

5.2 Simulation to Plant Communities of Different Types of Species

The weather conditions in the $Section 5.1$ is still used for this section to simulate the growth of three different plant communities composed of different species. The first plant community is composed of only short-rooted plants, which cannot draw the ground water. The second plant community includes short-rooted plants and long-rooted plants while the third plant community is made up of short-rooted plants and phytohormones-releasing plants. The values of initial biomass for these three plant communities are set to be the same. As shown in Figure 9,10 and

11, the WUE of groundwater is maximized in plant community 3 since the biomass of plants which can draw groundwater is the largest. In Figure 12, only the plant community 3 survives to the end of this year, while the dead point of plant community 2 is lagged comparing to plant community 1 due to the ability of drawing groundwater of long-rooted plants. Therefore, we can get some basic conclusions,

- The existence of long-rooted plants and photohormones-releasing plants can improve the WUE by drawing groundwater, to feed the whole community surviving drought.
- The beneficial brought by phytohormones-releasing plants is significantly larger than long-rooted plants, since the phytohormones can improve the WUE of the plant community in nature.

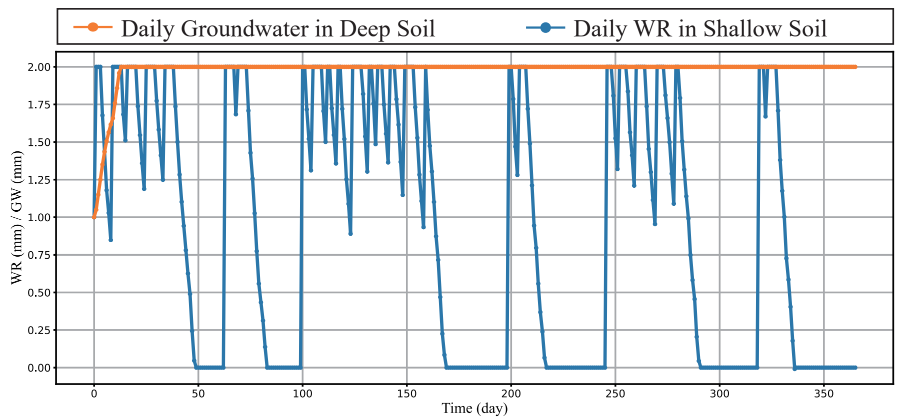


Figure 9: Daily WR and GW with the plant community 1

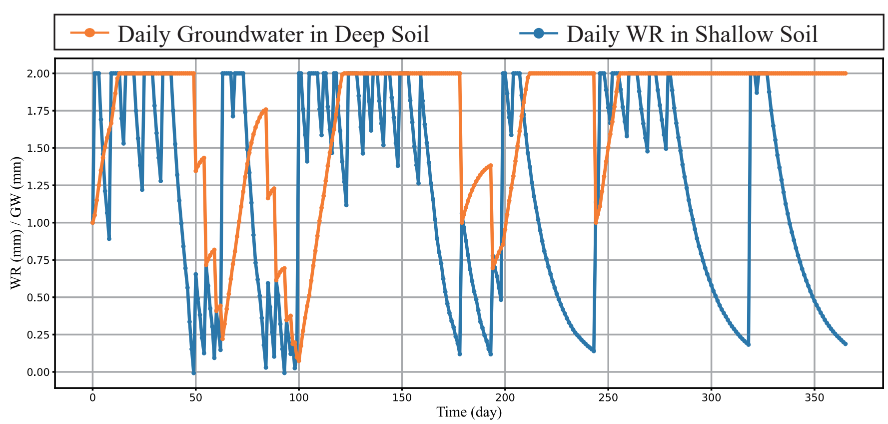


Figure 10: Daily WR and GW with the plant community 3

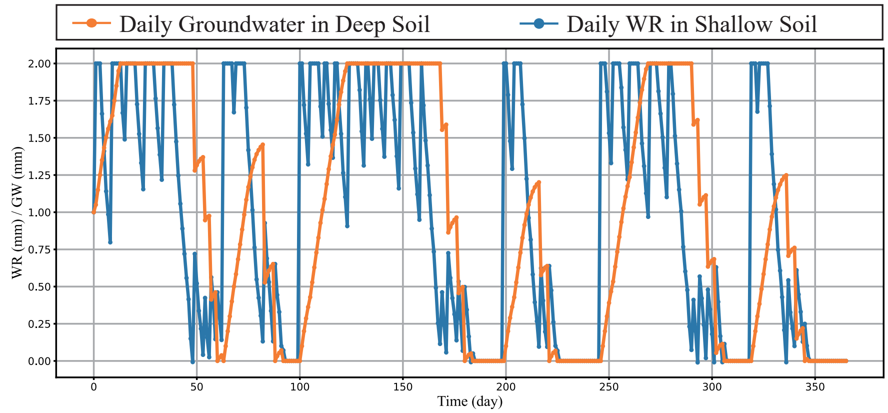


Figure 11: Daily WR and GW with the plant community 2

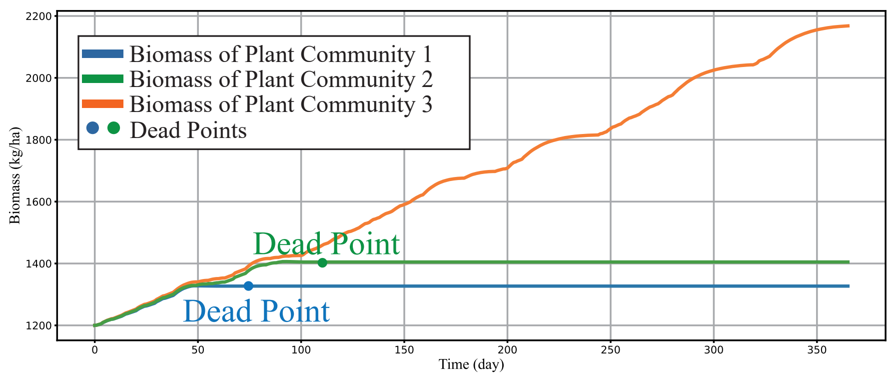


Figure 12: Biomass growth of different plant communities

5.3 Optimum Combination of Different Types of Species Adapting Drought

Through the discussion of the impacts of different types of species in a plant community, we can give the conclusion about how to benefit the adaptability of a plant community to drought through adjusting the types of species in the community,

- It's not true that the adaptability of a plant community to drought can be improved by only increasing the amount of any species in this community. The amount doesn't matter in the face of drought. It's the existence of types of species that could improve the WUE of the community that true matters a lot.
- The type of long-rooted plant and phytohormones-releasing plant are preferred in this paper to overcome drought. The WUE of the whole community can be improved so that all

plants could still to survive.

- The type of phytohormones-releasing plant works best in improving WUE. The combination of phytohormones-releasing plants and any other plants is capable of surviving long-term and irregular drought.

6 Sensitivity to Various Weather Conditions

To assess sensitivity to various weather conditions, the model is run under the Low frequency drought, high frequency drought and prolonged. In these three experiments, the factors related to the drought level are precipitation, temperature, PLE, PAR. Moreover, the variation of PLE and PAR are largely related to temperature. Therefore, to demonstrate more intuitively how drought affects community changes, we simulated the severity of drought by controlling rainfall and temperature. The specific values of temperature and precipitation during drought or non-drought are still generating using Table 2. In Figure 13,14 and 15, the weather of a control group (Orange dash-dot line and blue dash-dot line) and the weather of an experimental group (purple dot-straight line and green dot-straight line) are plotted to display different climate conditions. The plant community selected in this experiment is the community including short-rooted plants and long-rooted plants. From Figure 16, the plant community under any climate condition is dead before $150\ days$. Some conclusions regarding how climate conditions impact the growth of a plant community can be summarized as follows,

- The negative impacts of different climate conditions can be sorted from the most negative to the least negative: **Drought of higher duration** $>$ **Drought of higher frequency** $>$ **Drought of normal level** $>$ **drought of lower frequency**

- The conclusions in the optimum combination of types of plants to adapt to drought is valid regardless of various climate conditions, which means that **long-rooted plants and phytohormones-releasing plants still functions in improving WUE of the whole community**.

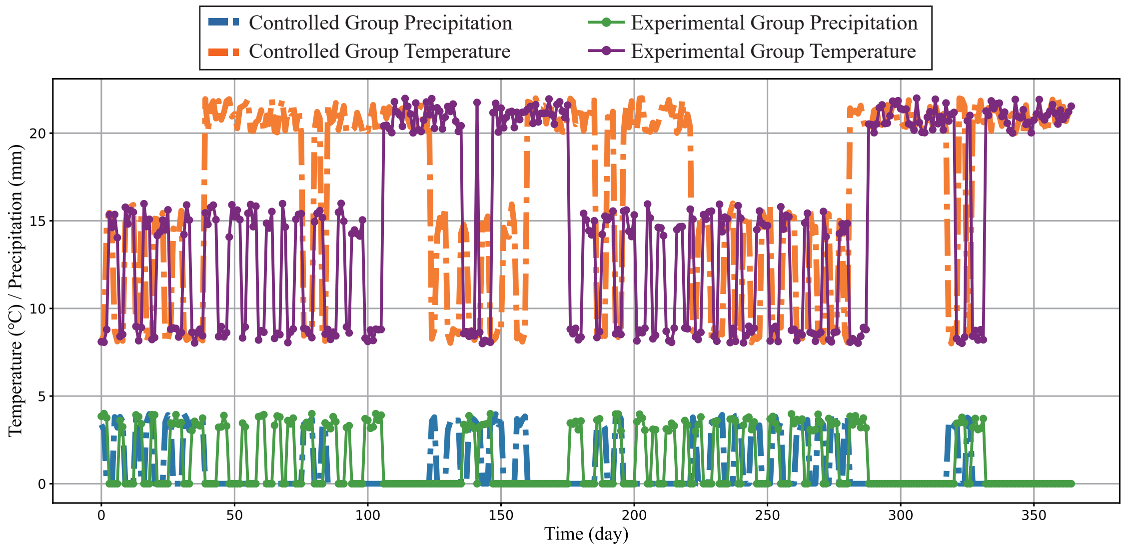


Figure 13: Climate Condition: Lower drought frequency vs controlled drought frequency

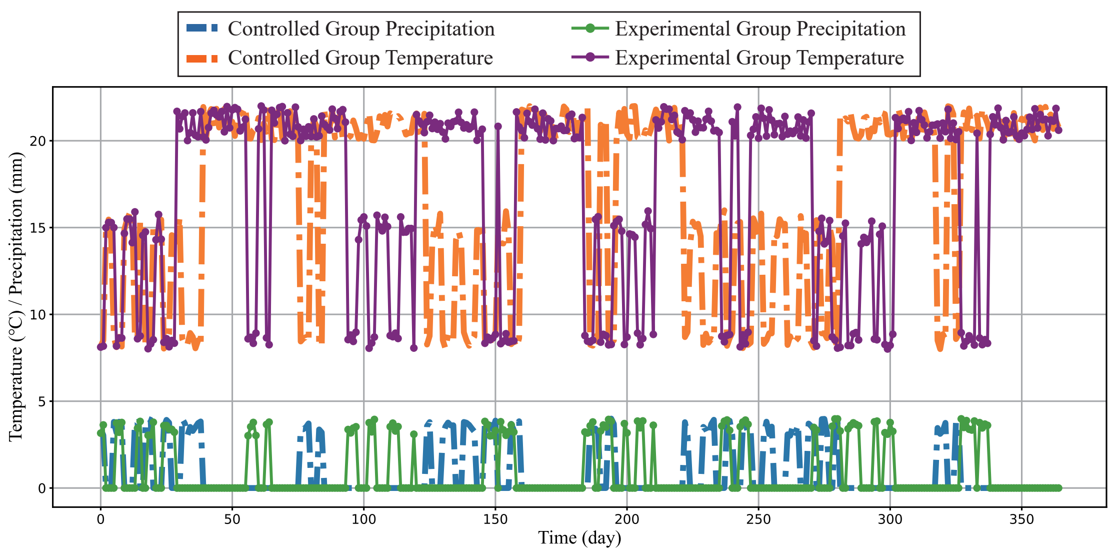


Figure 14: Climate Condition: Higher drought frequency vs controlled drought frequency

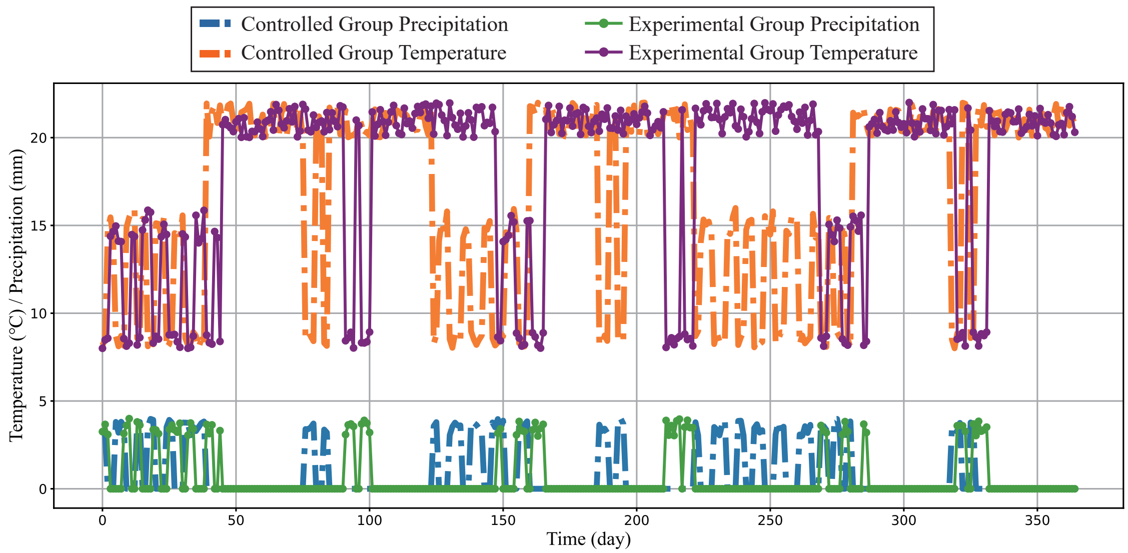


Figure 15: Climate Condition: Higher drought duration vs controlled drought duration

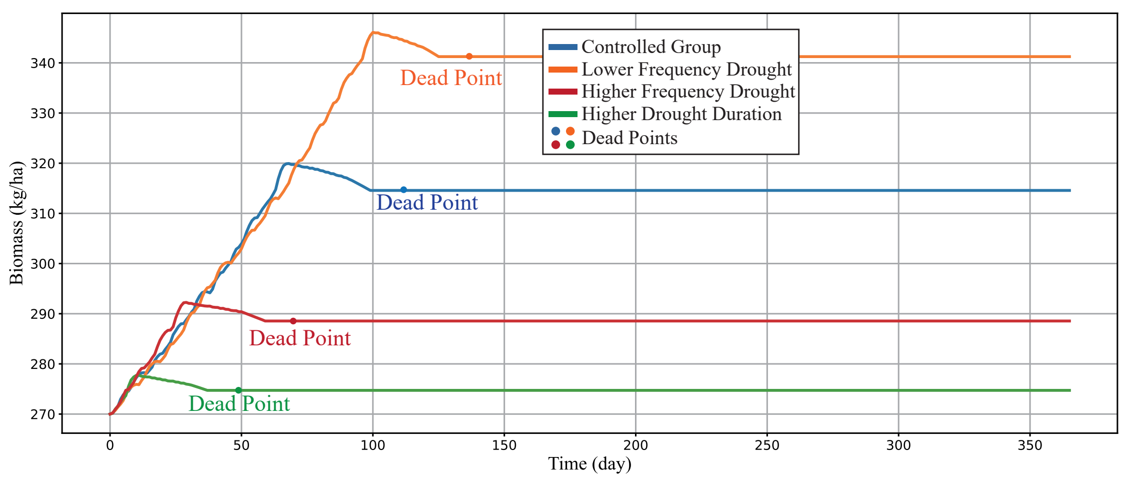


Figure 16: Growth of biomass: Three different climate conditions in (a), (b) and (c) vs controlled climate condition

7 Model Modifications to Adapt to Environment Pollution and Habitat Reduction

In this section, PGPC model is further modified to take the environment pollution and habitat reduction into consideration. According to the logic of the modelling process of our model PGPC, we can model these two factors into two reducers as we do in $Section 4.3$,

$$\Gamma_i = R_{red} T_{red,i} W_{red} P_{red} H_{red} \tag{10}$$

where P_{red} and H_{red} are the reduction from environment pollution and habitat reduction respectively. The explicit form of these two factors are given in Online Appendix considering the simplicity of this paper. The simulation results of the impacts of these two factors on the growth of a plant community are provided in the following.

7.1 Environment Pollution

The climate condition of this simulation is identical to $Section$ 5.1 and the plant community tested here is composed of short-rooted plants, long-rooted plants and photohormones-releasing plants.The simulation set the community free from environment pollution as the control group and the community suffering environment pollution as the experiment group. The simulation results are given in Figure 17. From this figure, it's obvious that the difference between the biomass of these two communities caused by environment pollution. One thing should be noted is that the difference caused by environment pollution is smaller comparing to the community composed of only short-rooted plants since the strength of the purifying effect of green plants is highly related to their biomass. Hence, we can draw the conclusion that **the plant community composed of the optimum combination of species is more resistant to environment pollute than the community composed of only short-rooted plants**.

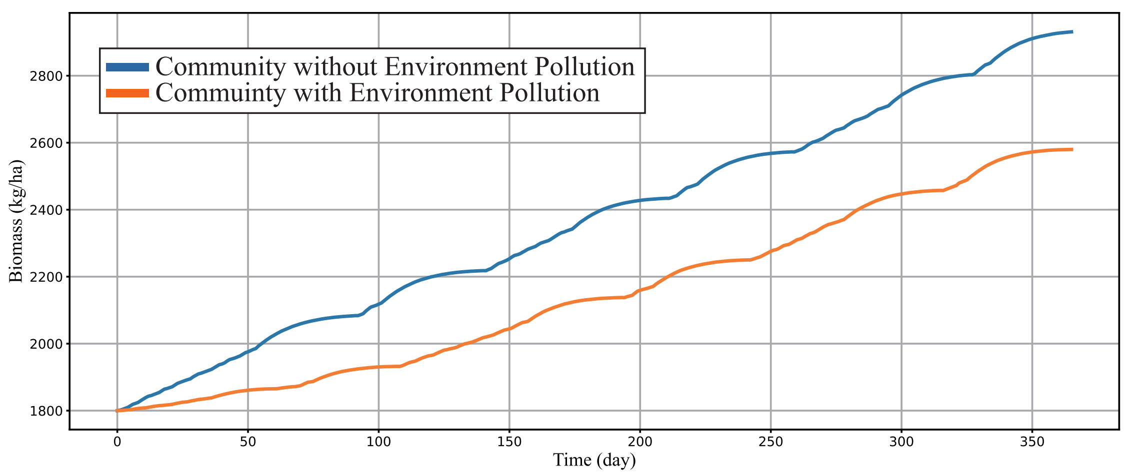


Figure 17: Impacts of environment pollution on the growth of a plant community

7.2 Habitat Reduction

The climate condition and the plant community used here are the same as simulation for environment pollution. The community free from habitat reduction is set as the control group and the community suffering habitat reduction is set as experiment group. The impact of habitat reduction is indicated in Figure 18, where the difference is the same among other simulation with different communities as control group. Hence, the conclusion is that **The diversity of species in a plant community has no difference to the resistant to the habitat reduction**

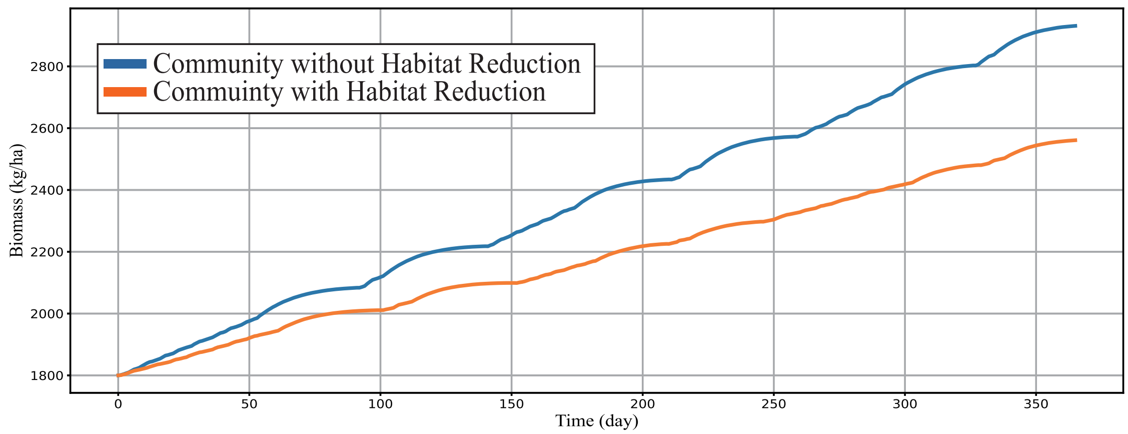


Figure 18: Impacts of habitat reduction on the growth of a plant community

8 Recommendations

The graph of plant species interactions (Figure 5) and the analysis of the results (Section 6) allow us to give the following recommendations to ensure the long-term viability of a plant community.

1. **Avoid planting a single plant species.** For plant communities composed of a single plant species, the biological energy lost under drought conditions cannot be compensated by other means because of the lack of multiple strategies to cope with drought. As a result, the resistance and survival of the whole community is poor.

2. **Mixed planting of multiple types of plants.** In the figure 16, the total biomass of plants of mixed species is more than that of single species. Long-rooted plants increase the water use efficiency of the plant community by drawing water from deeper soil layers. The presence of drought-resistant species increases plant community insurance against drought and, hence, is important for the functioning of grassland ecosystems.

3. **Planting plant species that release phytohormones is a preferred choice over long-rooted plants.** Based on the comparison of the graph results, the total biomass of plants grown to release hormones was slightly more than that of long-rooted plants. At the same time, there was an increase in the total root length of the plant community due to the influence of phytohormones, which improves the overall water use efficiency and thus become more resistant to drought.

Mixed planting in a larger environment can significantly improve the WUE of the plant community, and the richer species can make full use of the various resources in the environment, effectively improving the stability and resistance of the community and enriching biodiversity.

9 Strengths and Weaknesses

9.1 Strengths

- The PGPC model is formulated on a certain **theoretical basis**. After reviewing related literature, we determined the parameters and functions carefully. Meantime, all inputs based on **real-world data** from trusted websites and governmental agencies. Therefore, our model is scientific and reasonable.
- The main strength is its **enormous extensible** and including **reality factors** into a robust framework. For instance, for the plant community, we take the photosynthesis, precipitation, groundwater and temperature into account. Therefore, this model can be applied in bigger environment.
- The **delicate images** are also a great advantage of our paper, such as the Water cycle figure, comparison chart of the three stakes and figure of biomass growth etc. These figures help explain complex principles.
- Under various weather conditions, our model still yields reasonable results, which prove the **adaptability** and **robustness**.

9.2 Weaknesses

- More factors, such as microorganisms and nitrogen, can be considering into the model if we have more complete data and related theoretical studies.

- Our model simulations are limited to herbaceous plants in arid regions. In addition, we only considered the mutually beneficial symbiotic relationship between the two plants, ignoring the competitive relationship that exists between different species of plants, which needs further research.

- Some assumptions are applied to model the drought condition, which may lead to the situation contrary to the real and random weather condition.

10 Conclusion

We construct the PGPC model to predict the changes of a plant community over time. We take into account three factors, namely self-factors, abiotic factors and interaction between different species, to simulate the actual changes of a plant community in irregular weather cycles. Here, we list the final conclusions to all given tasks:

- At least two different types of plant species, namely long-rooted and photohormones-releasing plants, are required for the community to benefit and the existence of long-rooted plants and phytohormones-releasing plants can improve the WUE.

- The type of phytohormones-releasing plant works best in improving WUE. The combination of phytohormones-releasing plants and any other plants is capable of surviving long-term and irregular drought.

- The negative impacts of different climate conditions can be sorted from the most negative to the least negative: Drought of higher duration $>$ Drought of higher frequency $>$ Drought of normal level $>$ drought of lower frequency

- the plant community composed of the optimum combination of species is more resistant to environment pollute than the community composed of only short-rooted plants.

- The diversity of species in a plant community has no difference to the resistant to the habitat reduction.

References

[1] S. Naeem and S. Li, "Biodiversity enhances ecosystem reliability," *Nature*, vol. 390, no. 6659, pp. 507–509, Dec. 1997.

[2] P. Mariotte, C. Vandenberghe, P. Kardol, F. Hagedorn, and A. Buttler, "Subordinate plant species enhance community resistance against drought in semi-natural grasslands," *Journal of Ecology*, vol. 101, no. 3, pp. 763–773, May 2013.

[3] T. B. dos Santos, A. F. Ribas, S. G. H. de Souza, I. G. F. Budzinski, and D. S. Domingues, "Physiological Responses to Drought, Salinity, and Heat Stress in Plants: A Review," *Stresses*, vol. 2, no. 1, pp. 113–135, Feb. 2022.

[4] S. Haberstroh and C. Werner, "The role of species interactions for forest resilience to drought," *Plant Biology*, vol. 24, no. 7, pp. 1098–1107, Dec. 2022.

[5] T. Moulin, A. Perasso, and F. Gillet, "Modelling vegetation dynamics in managed grasslands: Responses to drivers depend on species richness," *Ecological Modelling*, vol. 374, pp. 22–36, Apr. 2018.

[6] T. Moulin, A. Perasso, P. Calanca, and F. Gillet, "DynaGraM: A process-based model to simulate multi-species plant community dynamics in managed grasslands," *Ecological Modelling*, vol. 439, p. 109345, Jan. 2021.

[7] S. E. Fick and R. J. Hijmans, "WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas," *International Journal of Climatology*, vol. 37, no. 12, pp. 4302–4315, Oct. 2017.

[8] A. Schapendonk, W. Stol, D. van Kraalingen, and B. Bouman, "LINGRA, a sink/source model to simulate grassland productivity in Europe," *European Journal of Agronomy*, vol. 9, no. 2-3, pp. 87–100, Nov. 1998.