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Effects of Flooding Duration and Growing Stage on Soybean Growth Based on a Multi-Year Experiment

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Abstract: Flood stress on crops severely constrains food production. From 2011 to 2018, a plot test was conducted to investigate the effects of flooding duration and growth stage on soybean plant height, the number of solid pods, 100-grain weight, yield, and dry matter mass, and their interannual variation. The results showed that the soybean indicators were significantly influenced by the year, flooding duration and growth stage, and their interaction. Under the same flooding duration and growth stage, the smallest plant height, number of solid pods, 100-grain weight, and dry matter mass were observed in 2016; and the largest plant height, number of solid pods, yield, and dry matter mass were observed in 2011. The soybean critical flooding duration for the number of solid pods, yield, and dry matter mass was 3 days, and that for 100-grain weight was 6 days. The flooding duration had no significant effect on plant height. The flooding-sensitive growth stage for soybean plant height and dry matter mass was the seedling stage, and that for the number of solid pods, 100-grain weight, and yield was the flowering-podding stage. When investigating the effects of flooding stress on soybeans, the impacts of interannual variation such as high temperatures and drought on soybean growth and yield should be integrated.

Keywords: drought and flood; high temperature; interannual variation; waterlogging; yield

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1. Introduction

Crop flooding is one of the major constraints to food production [1]. Field flooding can create hypoxic soil conditions for a short period of time, limiting normal crop growth, and continued or repeated flooding results in reduced crop yields. Along with global climate change, extreme rainfall and high-temperature or drought events are increasing, the spatial and temporal distribution of rain and heat is increasingly imbalanced, and local flooding continues, aggravating the threat of flooding on food security [2]. According to statistics, from 2000 to 2018 the average annual crop yield in China was reduced by 9.61 million hm^2 due to flooding, of which 206.78 million tons of grain was lost due to the natural disasters in 2018. The transformation pattern of the production limitation of food and economic crops, which are mainly subject to superimposed stresses such as drought, flooding, or even high temperatures, presents a great challenge to China's food and economic security [3].

Soybean is an important grain and economic crop in China, and is rich in protein, vegetable oil, and various phytochemicals [4]. Soybean growth is sensitive to water stress, requiring large amounts of water but not being tolerant to flooding, and is extremely susceptible to rainfall-induced flooding stress during growth, which in turn affects the yield [5,6]. Approximately 40% of the country's soybean cultivation area is located in the Huanghua Hai Plain, a typical flood- and drought-prone area in eastern China. This region is prone to flooding and high-temperature heat damage during the summer soybean growth period, limiting high and stable soybean yields. Therefore, an investigation into the soybean flooding stress pattern and its influencing factors will provide important theoretical support to optimize and improve the consistency of soybean yields.

The flooding duration and growth stages are important direct flooding factors that affect soybean growth [7,8]. Short-term flooding stress at the seedling stage does not have a significant effect on soybean growth and yield, but after more than 10 days of flooding, the number of solid pods per plant and yield decreases significantly, and the longer the flooding period, the greater the decline [9]. The flooding of summer soybeans during the flowering stage reduces the number of solid pods per plant, the number of grains per pod, the weight of grains per plant, and the weight of 100 grains, resulting in a reduction in yield [10]. Studies on flooding in other crops have found that high-temperature stress during flooding aggravates the reduction in cotton yield and the root vigor of cotton plants [11,12]. A study on cotton after drought found that the effects of drought and flooding on crop growth and yield were significantly different from the effect of single flooding, and that flooding later in the season had a compensatory effect on earlier drought conditions [13]. To fully evaluate the effects of flooding on soybean growth, it is necessary to explore not only the influence of direct factors such as flooding duration and changes in growth, but also the influence of indirect factors unrelated to inundation, such as drought and high temperature.

Soybean flooding studies have mostly focused on short-term experiments with a single direct flooding factor, and there are few studies that have comprehensively integrated the effects of multiple factors on soybean growth. To explore the influence of the actual meteorological environmental factors and the direct effects of flooding on soybean growth, those factors were monitored for their effects on physiological indicators and yield of soybeans over multiple years.

2. Materials and Methods

2.1. Overview of the Study Area

The experiment was conducted at the Xinmaqiao Agricultural and Water Comprehensive Experimental Station in Bengbu City, Anhui Province. The station is located at the southern end of the Huanghuaihai Plain (33°09′ N, 117°22′ E; 18 m a.s.l.). It is in a transition zone between the northern subtropical and warm temperate climates. The soil of the experimental station is a silty clay between the depths of 0–2 m, and it is the most widely distributed medium- and low-yield soil in the Huanghuaihai Plain. The average annual rainfall is 902.7 mm, and the rainfall during the flood season from June to September accounts for about 50% to 70% of the total annual precipitation. The groundwater depth in the flood season varies from 0 to 1.3 m. The main crops grown in the study area are corn, soybean, and wheat.

2.2. Experimental Design

The soybean flooding experiment was carried out from 2011 to 2018. Each year, two direct factors of flooding affecting crop growth, i.e., flooding duration and growth stage, were included. The treatment without flooding during the whole growth period was set as a control (Table 1). Three flooding growth stages were mainly investigated: seedling stage, branch stage, and flowering-podding stage. Flooding duration was predominantly examined at three levels: 3 days, 6 days, and 9 days, with interannual fine-tuning of the number of days. Interannual changes in meteorological conditions were classified as the indirect factor of flooding effect (Figures 1 and 2). Each treatment was repeated and then randomly arranged within the test plot, in which each treatment was repeated twice in 2011–2015, three times in 2016–2017, and four times in 2018. A surface flooding depth of 10 cm was maintained during the soybean flooding period. The groundwater depth was reduced to 30 cm below the surface within 2 days after flooding, and further reduced to 80 cm on the fourth day; the groundwater depth was maintained at about 1.5 m during the non-flooded period. The start time of soybean flooding was synchronized with natural rainfall to give the experiment a high degree of field simulation [9–11]. After the soybeans reached maturity, each test plot was harvested separately for yield measurements.

Table 1. Experimental design of soybean flooding duration and growth stage.

2011		2012		2014		2015	2016	2017	2018
Seedling Stage	**Branch Stage**	**Seedling Stage**	**Branch Stage**	**Branch Stage**	**Flowing-Podding Stage**	**Flowing-Podding Stage**	**Flowing-Podding Stage**	**Flowing-Podding Stage**	**Flowing-Podding Stage**
3 d		3 d		3 d		3 d	2 d	3 d	3 d
5 d		6 d		6 d		5 d	4 d	6 d	6 d
7 d		9 d		9 d		7 d	6 d	9 d	9 d
	3 d		3 d		3 d		8 d		
	5 d		6 d		6 d				
	7 d		9 d		9 d				

Control (no flooding throughout the growth period).

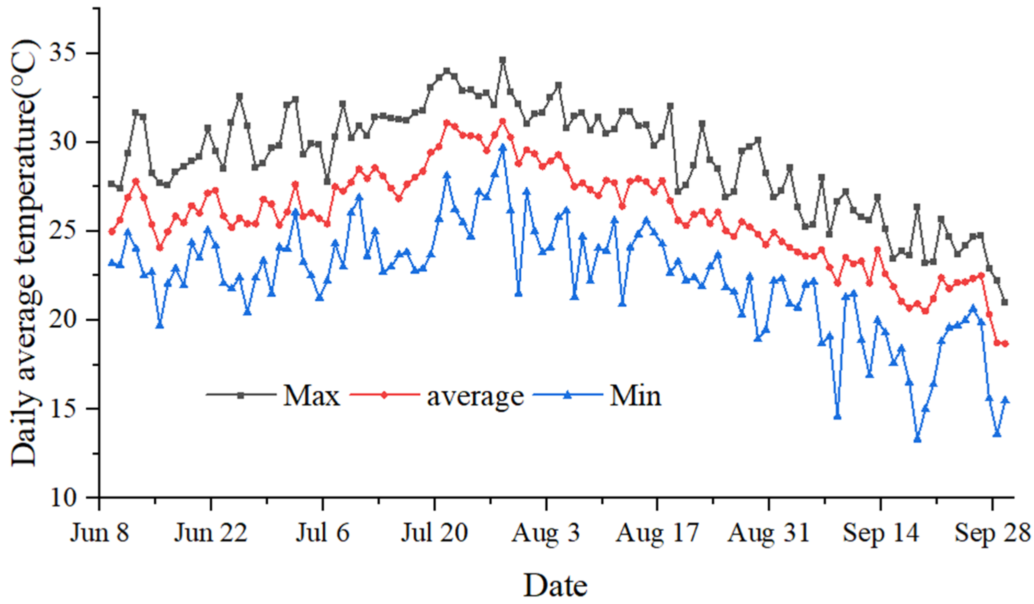

Figure 1. The multi-year maximum, average, and minimum of daily average temperature.

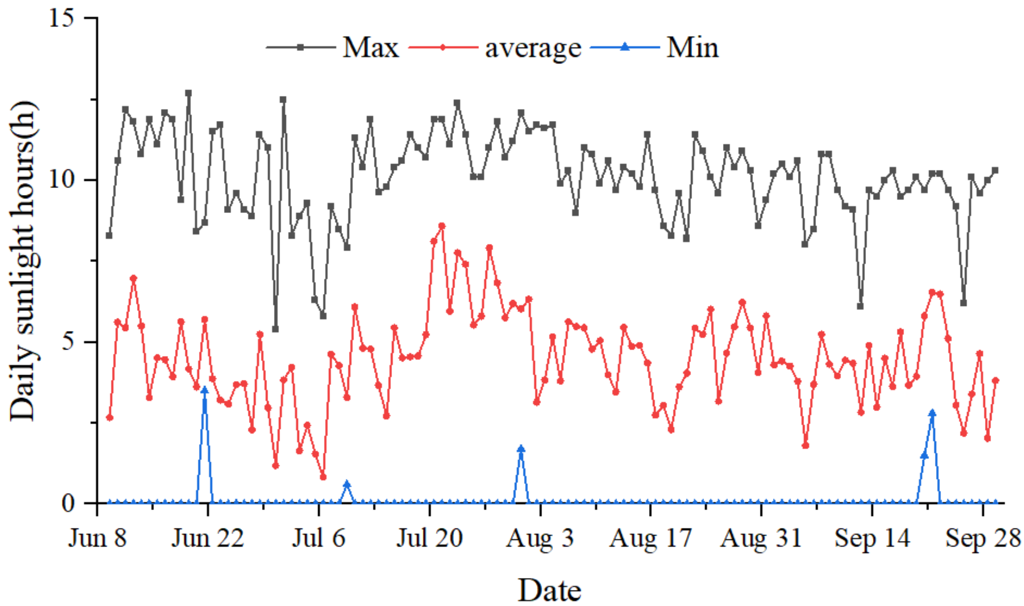

Figure 2. The multi-year maximum, average, and minimum of daily sunlight hours.

Each test plot had a surface area of 2.0 m^2, soil depth of 2.0 m, and a 30 cm sand filter layer at the bottom. The water level in the plot was automatically controlled by a computerized control system with a control range of 0.1 m above the surface to 2.3 m below the surface. Each plot was isolated along the sides and bottom by steel frames extending 10 cm above the soil and a glass canopy above the plot isolated it from natural rainfall. After wheat was harvested, soybeans (variety "Zhong Huang 13") were sown in mid-June at a seedling density of 329,000 plants/hm^2 and harvested in late September. The application rate of base fertilizer was 225 kg/hm^2, of which N, P_2O_5, and K_2O each accounted for 15%, and no top fertilizer was applied during the growth period.

2.3. Data Measurement and Analysis

When soybeans were matured, the plant height, dry matter mass, number of solid pods, 100-grain weight, and yield were measured for each plot. Three representative plants were selected from each test plot to measure the plant height with a tape measure. For the three representative plants, the stems, leaves, fruits, and roots were separated. After exposure to 105 °C for 0.5 h, the plant parts were then dried at a constant temperature of 80 °C to a constant weight, and then weighed for dry matter mass. Three representative plants were selected from each test plot for indoor seed testing, and their pod number, 100-grain weight, and seed yield were determined by direct measurements.

Statistical analysis software SPSS 17.0 was used to analyze the variance (ANOVA) of the experimental data, and the least significant difference (LSD) method was used for significance testing. Duncan's test was used for multiple comparisons between treatments, and a *t*-test was used to compare the differences among interannual data. All statistical tests were performed at a significance level of $p = 0.05$.

3. Results

3.1. Plant Height

The influence of year and growth stage on soybean plant height was significant, while the flooding duration had no significant effect (Table 2). The interaction between year and growth stage significantly affected soybean plant height, while the interaction between flooding duration and year or growth stage did not. The interaction of year, growth stage, and flooding duration on soybean plant height was very significant.

Table 2. Effects of year, flooding duration, and growth stage on soybean plant height.

Treatment	Significance of Differences
Year	0
Flooding duration	0.361
Growth stage	0
Year × Growth stage	0.026
Year × Flooding duration	0.649
Growth stage × Flooding duration	0.317
Year × Growth stage × Flooding duration	0

The variation in soybean plant height for different flooding durations and growth stages from 2011 to 2018 showed clear interannual variation in soybean plant height (Figure 3), and the interannual difference in flooded treatments was similar to that of the control. For example, the plant height was smallest in 2016 and largest in 2011. There was a clear interaction between the effects of years and growth stages on soybean plant height; the plant height at the seedling stage was greater in 2011 than 2012, the plant height at the branch stage in 2011 was significantly larger than that in 2012 and 2014, and the plant height in the flowering-podding stage was the smallest in 2016 and the largest in 2015. This indicates that soybean plant height was significantly influenced by the year and its interaction with the growth stage.

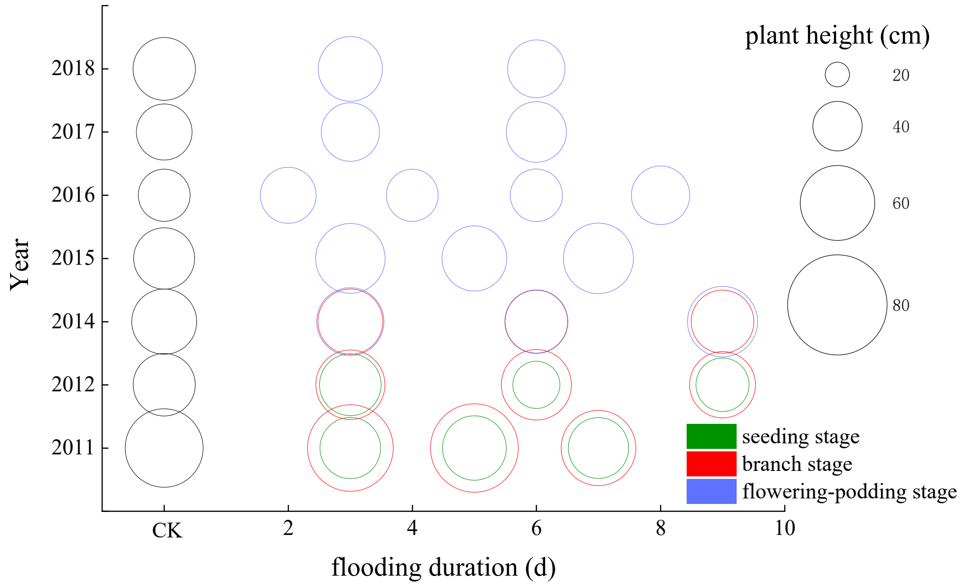

Figure 3. Effects of year, flooding duration, and growth stage on soybean plant height.

Consistent with the statistical results, neither the flooding duration nor its interaction with the growth stage or year had a significant effect on soybean plant height (Figure 3). Under the same year and growth stage, an increase of flooding duration did not show a significant negative effect on soybean plant height compared with the control group. This indicates that flooding duration had little effect on soybean plant height.

The change in flooding growth stage clearly affected soybean plant height. Taking the flooding duration of 9 days as an example, the soybean plant height at the seedling stage < branch stage < flowering-podding stage accounted for 81.4% < 100.9% < 111.7% of the control's values, respectively (Figure 3). There was a significant interaction between the growth stage and year on soybean plant height. In 2011 and 2012, plant height at the flooding branch stage was greater than that in the control, with average changes of 106.3% and 109.9%, respectively. The plant height at the seedling stage was lower than that of the control treatment in both years, and the average change rates were 79.2% and 86.6%, respectively. The plant height at the branch stage in 2014 was slightly less than that at the flowering-podding stage. This indicates that the seedling stage is the most flood-sensitive stage affecting soybean plant height.

3.2. Number of Solid Pods

Three single factors, i.e., year, flooding duration, and growth stage, had very significant effects on the number of solid pods (Table 3). The interaction between year and flooding duration did not affect the number of solid soybean pods, while the interaction between growth stage and year or flooding duration had a significant effect. The interaction between year, growth stage, and flooding duration on the number of solid soybean pods was highly significant ($p < 0.0001$).

Table 3. Effects of year, flooding duration, and growth stage on the number of solid soybean pods.

Treatment	Significance of Differences
Year	0
Flooding duration	0
Growth stage	0
Year × Growth stage	0.016
Year × Flooding duration	0.427
Growth stage × Flooding duration	0
Year × Growth stage × Flooding duration	0

The interannual variation in the number of solid soybean pods is clear, and the interannual variation of the flooded treatments was consistent with that of the control (Figure 4). For instance, the number of solid pods was smallest in 2016 and largest in 2015. The effect of year and growth stage interaction on the number of solid pods was clear; the number of solid pods was significantly higher in 2011 than in 2012, when the seedling stage was flooded. When the branch stage was flooded for 3 days, the number of solid pods in 2011 and 2014 was significantly higher than that in 2012; as flooding lasted for more than 3 days, the number of solid pods in 2012 and 2014 was significantly higher than that in 2011. The number of solid pods was smallest in 2016 and largest in 2015, when the flowering-podding stage was flooded. The number of soybean pods is significantly influenced by both the year and its interaction with the growth stage.

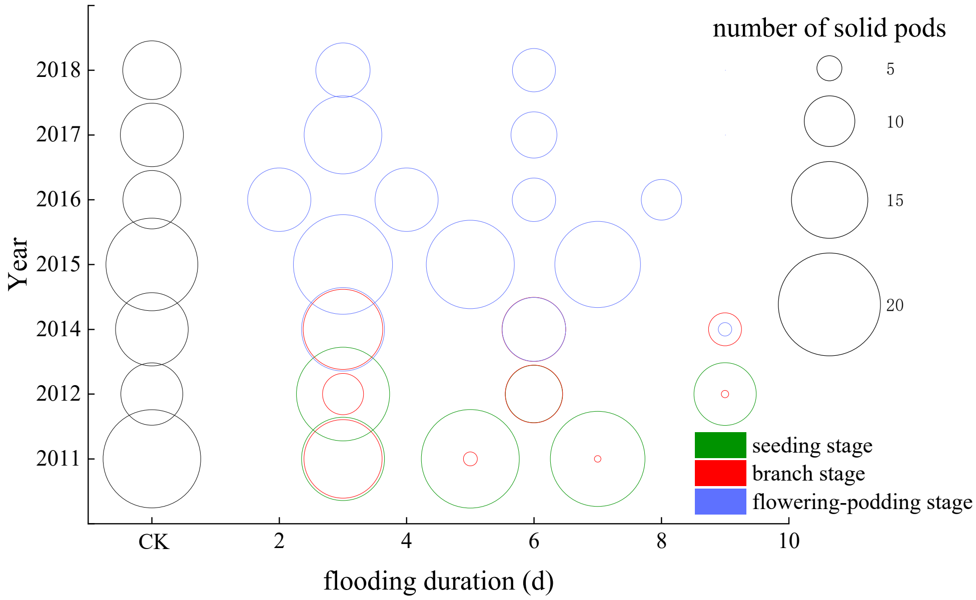

Figure 4. Effects of year, flooding duration, and growth stage on the number of solid soybean pods.

Consistent with the statistical results, the flooding duration and its interaction with the growth stage had clear effects on the number of soybean pods produced (Figure 4). In the seedling stage in 2011 and the branch stage in 2012, the number of solid pods on the third day of flooding was less than that of the control group. The number of solid pods subsequently increased, but was still less than that of the control group on the sixth day of flooding, and was significantly lower on the ninth day of flooding. At the seedling stage in 2012, the branch and flowering-podding stages in 2014, and the flowering-podding stage in 2015–2017, the number of solid pods was greater than that of the control group when flooded for 3 days, and they showed a declining trend when flooded for more than 3 days. In the branch stage in 2011 and the flowering-podding stage in 2018, the number of solid pods declined when flooded for three to nine days. This indicates that 3 days is the critical number of days for soybeans to be flooded before production is negatively affected.

The flooded growth stage had a significant effect on the number of solid soybean pods. Taking a flooding duration of 9 days as an example, the number of solid pods declined from the flowering-podding stage < branch stage < seedling stage, accounting for 17.6% < 21.4% < 98.8% of the control on average, respectively (Figure 4). There was a significant interaction between the growth stage and the year or flooding duration on the number of solid pods. In 2011 and 2012, the number of solid pods at the seedling stage was significantly greater than the corresponding value at the branch stage. In 2014, the number of solid pods at the branch stage within 6 days of flooding was slightly smaller than that at the flowering-podding stage, and the opposite was true at 9 days. In 2015–2018, the number of solid pods decreased with increased flooding duration. This indicates that the flood-sensitive growth stage for the number of solid soybean pods is the flowering-podding stage.

3.3. 100-Grain Weight

The 100-grain weight of soybeans was affected by year and flooding duration individually, but not by growth stage (Table 4). The interaction between year and flooding duration affected the 100-grain weight of soybeans significantly, while interactions between the growth stage and year or flooding duration did not. The interaction between year, growth stage, and flooding duration also had a significant impact on the 100-grain weight.

Table 4. Effects of year, flooding duration, and growth stage on 100-grain weight of soybeans.

Treatment	Significance of Differences
Year	0
Flooding duration	0
Growth stage	0.718
Year × Growth stage	0.914
Year × Flooding duration	0.013
Growth stage × Flooding duration	0.163
Year × Growth stage × Flooding duration	0

Changes in the 100-grain weight of soybeans at different flooding durations and growth stages from 2011 to 2018 are given in Figure 5. The interannual variation in 100-grain weight is observed. For example, the 100-grain weight of the control and flooded treatments in 2014 was consistently larger, while the 100-grain weight was smaller at the branch stage of 2012 and at the flowering-podding stage of 2016. There was a significant interaction between the year and flooding duration on the 100-grain weight of soybeans. For instance, the difference between the 100-grain weight in 2014 and 2012 under the submerged duration of the branch stage gradually weakened with increased flooding duration. This indicates that the 100-grain weight of soybeans was significantly affected by the year and its interaction with the flooding duration.

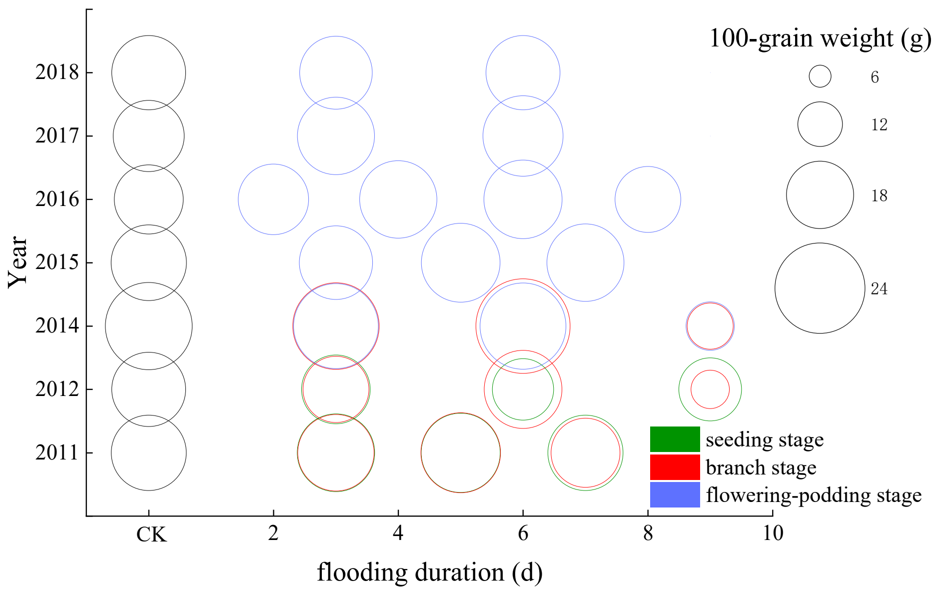

Figure 5. Effects of year, flooding duration, and growth stage on 100-grain weight of soybeans.

Consistent with the statistical analysis, the impact of flooding duration and its interaction with year on the 100-grain weight of soybeans was evident (Figure 5). During the seedling and branch stages in 2011, and the flowering-podding stage in 2016 and 2017, the 100-grain weight was greater than that of the control when flooded for 6 days, and the 100-grain weight presented a significant downward trend when it exceeded 6 days. The 100-grain weight at the seedling stage in 2012 decreased with increased flooding duration, and the decrease was greater when the number of flooding days exceeded 6 days. In the branch stage in 2012, the branch and flowering-podding stages in 2014, and the flowering-podding stage in 2015 and 2018, the 100-grain weight was slightly less than that of the control when flooded for 3 days, increased slightly when flooded for 6 days, and decreased significantly after 9 days. This indicated that 6 days was the critical number of days for the 100-grain weight of soybeans to be affected significantly.

The influence of flooding duration on the 100-grain weight of soybeans was not obvious. The 100-grain weight of soybeans in the same year and growth stage within 6 days of flooding did not change significantly compared with the control, and only the 100-grain weight in the flowering-podding stage reduced when flooded for 9 days. This indicates that short-term flooding in different growth stages has no clear effect on the 100-grain weight, but the 100-grain weight is affected when the critical number of flood days is exceeded. The 100-grain weights for the flowering-podding stage < branch stage < seedling stage account for 37.8% < 65.7% < 92.4% of the control, respectively. This indicates that the flood-sensitive growth stage for the 100-grain weight is the flowering-podding stage.

3.4. Yield

Considered individually, year, growth stage, and flooding duration all affected soybean yield significantly (Table 5). The interaction between year and growth stage or flooding duration had no significant effect on soybean yield, while the interaction between growth stage and flooding duration did. The interaction between year, flooding duration, and growth stage had a significant effect on soybean yield.

Table 5. Effects of year, flooding duration, and growth stage on soybean yield.

Treatment	Significance of Differences
Year	0
Flooding duration	0
Growth stage	0
Year × Growth stage	0.702
Year × Flooding duration	0.083
Growth stage × Flooding duration	0.047
Year × Growth stage × Flooding duration	0

There were clear interannual variations in soybean yield, with the variation in flooded treatments being consistent with that of the control (Figure 6). For example, the yield was lowest in 2012, and highest in 2011 and 2014. The interannual variation in soybean yield also depended on flooding duration and growth stage. The yield in 2012 at the seedling and branch stages was significantly lower than that in 2011 and 2014. The yield in 2018 was lowest when the flowering-podding stage was flooded for 3 days, and the yield in 2014 and 2015 was significantly higher than that in 2018. The maximum value was still in 2014 when the flowering-podding stage was flooded for 6 days. This indicates that soybean yield is significantly influenced by the year and its interaction with the flooding duration and growth stage.

Consistent with the statistical analysis, the flooding duration and its interaction with the growth stage significantly affected soybean yield (Figure 6). During the branch stage in 2012, the yield decreased at 3 days of flooding, increased at 6 days of flooding, and decreased significantly at 9 days of flooding. During the seedling stage in 2011 and 2012, the branch and flowering-podding stages in 2014, and the flowering-podding stage in 2015 and 2016, the yield was slightly higher than that of the control when flooded for 3 days and decreased significantly after 3 days. During the branch stage in 2011 and the flowering-podding stage in 2017 and 2018, the yield decreased with increased flooding duration. This suggests that 3 days is the critical number of flooding days to avoid a reduction in soybean yield.

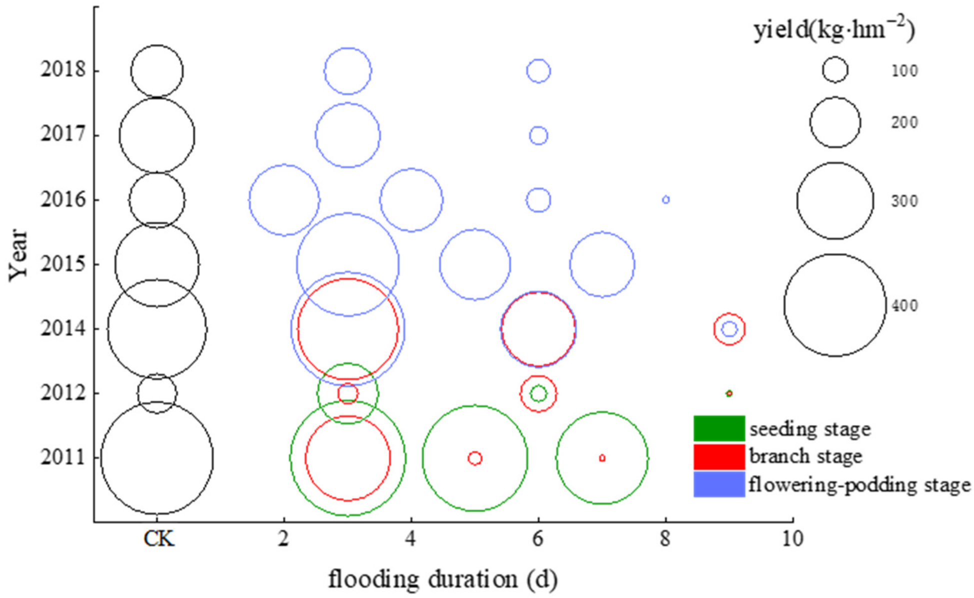

Figure 6. Effects of year, flooding duration, and growth stage on soybean yield.

Changes in the flooded growth stage significantly affected soybean yield. For 9 days of flooding, the order of yield was flowering-podding stage < branch stage < seedling stage, which decreased by 92.9% < 84.4% < 51.6%, respectively, compared with the control (Figure 6). There was a significant interaction between the growth stage and flooding duration on yield. In 2011 and 2012, the yield at the branch stage was lower than that at the seedling stage under different flooding durations, which decreased by an average of 66.2% and 27.3%, respectively, compared with the control. In 2014, the yield in the branch stage within 6 days of flooding was slightly lower than that in the flowering-podding stage, and the opposite was true when flooding lasted for 9 days. From 2015 to 2018, the yield decreased with increased flooding duration. This indicates that the most sensitive growth stage for soybean yield under flooding stress is the flowering-podding stage.

3.5. Dry Matter Mass

The three single factors—year, flooding duration, and growth stage—each had significant effects on the dry matter mass of soybeans (Table 6). The interaction between year and growth stage or flooding duration on dry matter mass was not significant, but the interaction between growth stage and flooding duration had a significant effect on dry matter mass. The interaction between year, growth stage, and flooding duration had a significant effect on dry matter mass.

Table 6. Effects of year, flooding duration, and growth stage on soybean dry matter mass.

Treatment	Significance of Differences
Year	0
Flooding duration	0
Growth stage	0.003
Year × Growth stage	0.517
Year × Flooding duration	0.05
Growth stage × Flooding duration	0.023
Year × Growth stage × Flooding duration	0

There were clear interannual variations in soybean dry matter mass (Figure 7). For example, the dry matter mass of the control and flooded treatments was the lowest in 2016 and higher in 2011. The dry matter mass in 2011 was significantly higher than that in 2012 when flooded at the seedling stage. The dry matter mass in 2018 was the highest when the flowering-podding stage was flooded for 3 days, and the maximum value changed in 2014 when flooded for 6 days. This indicates that soybean dry matter mass is significantly influenced by the year and its interaction with flooding duration and growth stage.

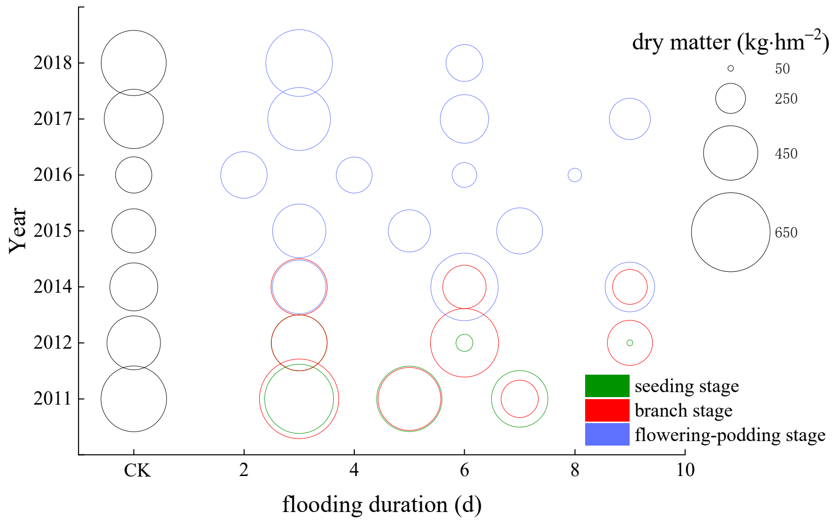

Figure 7. Effects of year, flooding duration, and growth stage on soybean dry matter mass.

Consistent with the statistical analysis, the flooding duration and its interaction with the growth stage significantly affected soybean dry matter mass (Figure 7). During the seedling and branch stages in 2011, the seedling stage in 2012, the branch stage in 2014, and the flowering-podding stage from 2015–2018, the dry matter mass was greater than that of the control when flooded for 3 days, and showed a significant decline when flooding exceeded 3 days. In the branch stage in 2012 and the flowering-podding stage in 2014, the dry matter mass was greater than that of the control when flooded for 3–6 days, and the dry matter mass decreased significantly after flooding for more than 6 days. This indicates that 3 days is the critical number of days for soybeans to be flooded to prevent declines in dry matter production.

The change in the flooded growth stage significantly affected the dry matter mass of soybeans. Taking the flooding duration of 9 days as an example, the order of soybean dry matter mass was seedling stage < branch stage < flowering-podding stage, accounting for 48.6% < 70.0% < 104.9% of the control on average, respectively. There was a significant interaction between the growth stage and flooding duration on dry matter mass. In 2011 and 2012, the dry matter mass at the branch stage was higher than that at the seedling stage. In 2014, the dry matter mass at the branch stage with different flooding durations was slightly lower than that at the flowering-podding stage. From 2015 to 2018, the dry matter mass decreased with increased flooding duration. This indicates that the sensitive growth stage for soybean dry matter mass under flooding stress is the seedling stage.

4. Discussion

4.1. The Influence of Interannual Factors on Soybean Growth and Yield

The influence of soybean flooding on plant height, the number of solid pods, 100-grain weight, yield, and dry matter mass has clear interannual differences, which can exclude the direct factors linked to flooding, such as flooding duration and growth stage. This study was conducted in the warm-temperate semi-humid monsoon climate zone of the Huaibei Plain, and the annual flooding test strictly controlled changes in the direct flooding factors. For different years, under uniform soil and crop variety conditions, the interannual changes in meteorological factors such as temperature and light should be the main indirect factors influencing the interannual variation in soybean growth and yield. For this reason, the number of high-temperature days ($\geq$35 °C), accumulated temperature, and cumulative hours of sunlight were counted for the entire period of crop growth. Among them, the annual total number of high-temperature days for the whole growth period was 2014 < 2011 < 2015 < 2017 = 2016 = 2012 < 2018. Although 2018 had the greatest number of high-temperature days, and its average maximum temperature was 36 °C, the average maximum temperatures of 2012 and 2016 rose to 36.6 °C and 36.3 °C, respectively. This is consistent with the smallest soybean plant height, number of solid pods, yield, and dry matter mass in 2016; the lower number of solid pods, yield, and dry matter mass in 2012; and the largest soybean plant height, number of solid pods, yield, and dry matter mass in 2011, when the number of high-temperature days and the average temperatures were lower.

The cumulative temperatures across the whole growth period were 2011 < 2015 < 2014 < 2016 < 2017 < 2012 < 2018, and the cumulative sunlight hours across the whole growth period were 2014 < 2011 < 2015 < 2012 < 2017 < 2018 < 2016. The interannual order of accumulated temperature and hours of sunlight was opposite to the interannual variation in soybean plant height, number of solid pods, 100-grain weight, yield, and dry matter weight, where the cumulative hours of sunlight and 100-grain weight were significantly negatively correlated. Therefore, high temperature may be an indirect factor that exacerbates soybean flood stress.

Studies on other crops have also shown that high temperatures significantly affect crop growth [11]. When cotton was under the stresses of high temperature, this caused a significant reduction in seed cotton yield in a trial where cotton was flooded in a concrete-bottomed measuring cylinder in the middle and lower reaches of the Yangtze River [12]. Furthermore, a barrel experiment used to set different levels of flooding and high temperatures at the cotton seedling stage found that these two factors aggravated declines in cotton root activity [14]. Previous studies have predominantly focused on crops such as cotton or rice, and few studies have focused on the influence of high temperatures and other meteorological environmental factors on soybean growth and yield. This study combined years of experiments analyzing high-temperature data and found that the flooding effect of soybeans is influenced not only by direct factors, such as flooding duration and growth stage, but also by indirect factors such as meteorological conditions changing with interannual flooding. In particular, the superposition of high-temperature factors could change soybean flooding response patterns.

4.2. Influence of Flooding Duration on Soybean Growth and Yield

The impact of flooding duration on the number of soybean pods, 100-grain weight, yield, and dry matter mass was significant, but was not so on plant height. Considering the interaction between the year and growth stage, the variation in soybean indicators with flooding duration presented three trends. The first trend occurred at the branch stage in 2011 and the flowering-podding stage in 2017 and 2018, where all soybean indicators excluding plant height decreased with increased days of flooding, and the decrease was more pronounced for longer days of flooding. Judging from the control treatments, which were not flooded throughout the entire growth period, all indicators were relatively large in these three years, indicating that soybean growth was less restricted by other indirect factors, such as drought or high temperature. Solely under the condition of flooding stress, the number of solid soybean pods and the 100-grain weight decreased as the duration of flooding increased, resulting in a decrease in yield [7,15]. Considering that all indicators of soybeans in the control treatment decreased in the remaining years, the two changing trends in those years were likely the result of the combined effects of indirect factors, such as drought or high temperatures [16].

The second variation trend occurred at the seedling stage in 2012, the branching and flowering-podding stages in 2014, and the flowering-podding stage in 2015–2016. Excluding plant height, all soybean indicators increased when flooded for 3 or 6 days, and only decreased significantly when flooding was prolonged. The reason may be that short-term flooding alleviated the impact of indirect factors such as drought or high temperatures on soybeans, which was similar to the compensatory effect of cotton flooding on early drought stress [13]. For instance, in 2016, when the average high temperature and quantity of sunlight were relatively large, all soybean indicators in the non-flooded control treatment were relatively small, indicating that soybeans were likely to be in a state of drought or high-temperature stress. At this time, the flooding had mitigated the impact of this stress, and the crop itself had some tolerance to flooding. Therefore, short-term flooding improves the number of solid pods, 100-grain weight, yield, and dry matter mass of soybeans. However, when flooding is prolonged, soybean organ growth is restricted, which leads to a significant decrease in dry matter accumulation and yield. At this time, high temperatures or drought stress will further aggravate the flooding stress.

The third trend occurred at the branch stage in 2012, when all soybean indicators excluding plant height decreased at the third day of flooding, increased at the sixth day of flooding, and decreased again at the ninth day of flooding. Because the number of solid pods and yield of the control in 2012 were significantly lower than those of other years, it can be speculated that soybeans may have been under the stress of indirect factors, such as drought or high temperature. The yield-reducing effect of soybean flooding on day three may be stronger than the yield-increasing effect of drought or high-temperature mitigation, resulting in a decrease in soybean yield. When flooding continued for 6 days, the yield-reducing effect of flooding may have been weaker than the yield-increasing effect of drought or high-temperature mitigation, resulting in a recovery in soybean yield. After flooding for more than 6 days, the number of solid pods, 100-grain weight, yield, and dry matter mass of soybeans were significantly reduced, due to prolonged flooding.

In summary, when flooded for $\leq$3 days, the number of solid pods, yield, and dry matter of soybeans were similar to those that were not flooded. When flooded for $\leq$6 days, the 100-grain weight of soybeans was almost unaffected by flooding. Therefore, the critical flooding duration for the soybean pod number, yield, and dry matter mass is 3 days, and the critical flooding duration for 100-grain weight is 6 days. Flooding within the critical duration may alleviate the drought or high-temperature stress of soybeans, and the impact of soybean flooding beyond the critical duration is likely to be amplified by indirect factors such as high temperature or drought.

4.3. Effects of Flooded Growth Stage on Soybean Growth and Yield

The changes in the flooded growth stage had significant effects on soybean plant height, the number of solid pods, yield, and dry matter mass. In contrast, while 100-grain weight was not sensitive to the influence of the flooded growth stage, it decreased significantly when the soybean plant was flooded for more than 6 days at the flowering-podding stage. Flooding at the seedling stage had the greatest impact on soybean plant height and dry matter mass; flooding at the flowering-podding stage had the greatest impact on the number of solid pods, 100-grain weight, and yield; and flooding at the branch stage had the lowest impact on various soybean indicators. Flooding at the seedling stage, when soybeans are in the stage of vegetative growth, predominantly affects soybean plant height, which then leads to a decrease in soybean dry matter [17]. Once the flooding stress is relieved, the roots and leaves continue to grow in the seedling stage and have enough time to recover, so flooding at the seedling stage has little long-term effect on flowering, pod production, and yield [18]. Flooding stress during the branch stage may promote the vegetative growth of soybean straw, so it has little effect on the physiological indicators and yield of soybeans. In contrast, the flowering-podding stage is the most nutrient-demanding stage in soybean growth, and waterlogging through prolonged flooding will cause the soybean root system to gradually decline. With prolonged flooding, the soybean root system function decreases, and the flower pods fall off, eventually leading to a significant decrease in soybean yield [19,20]. Therefore, the flood-sensitive growth stage for soybean yield, the number of solid pods, and 100-grain weight is the flowering-podding stage.

5. Conclusions

(1) The year and its interaction with flooding duration and growth stage had significant effects on soybean indicators. Under the same flooding duration and growth stage, soybean plant height, the number of solid pods, 100-grain weight, and dry matter mass were the lowest in 2016, and the plant height, number of solid pods, yield, and dry matter mass were highest in 2011.

(2) The critical flooding duration for the number of solid pods, yield, and dry matter mass is 3 days, and the interaction between flooding duration and growth stage is significant. The critical flooding duration for 100-grain weight is 6 days, and the interaction effect of flooding duration and year was significant. The effect of flooding duration on plant height was not significant.

(3) The flood-sensitive growth stage for soybean plant height and dry matter mass is the seedling stage. Taking the flooding duration of 9 days as an example, the size of dry matter mass was seedling stage < branch stage < flowering-podding stage. The flood-sensitive growth stage for 100-grain weight, the number of solid pods, and yield is the flowering-podding stage. For instance, at 9 days of flooding, the yield size was flowering-podding stage < branch stage < seedling stage, and the yield was reduced by 92.9% < 84.4% < 51.6%, respectively, relative to the control.

(4) Short-term flooding has no significant effect on soybean growth and yield. When the critical flooding duration is exceeded, however, soybean growth and yield are significantly reduced, and high temperatures or drought stress will amplify the reduction of growth and yield. When considering the effects of crop flooding stress, the effects of interannual changes in indirect factors such as high temperature and drought on soybean growth and yield should be integrated.

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