Altered climate dynamics in the East-European forest-steppe incites fruit plants injury

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Abstract. Temperature and precipitation regimes in the East-European forest-steppe have been disrupted in response to the recent climatic changes. Particularly, (1) increased the range of day-night temperatures, especially during the spring – summer period, (2) increased the number and intensity of thaws in January – February, and (3) the timing, range and intensity of annual precipitation were distorted, thus making some periods of the year excessively dry or wet. Synergistically, these disturbances (1) increase environmental stress to fruit plants, and (2) alter conditions for their growth, development and crop bearing. Hence, we argue that current criteria for the selection of plant varieties for cultivation in that region are no longer valid, and the stress-specific adjustment to these criteria is required.

1. Introduction

Regional selection of fruit plant varieties has been essentially limited by climatic conditions, and temperature and precipitation regimes are the primary indices for cultivation of a particular fruit crop [1, 2]. Climatic changes, particularly those associated with accumulation of anthropogenic greenhouse gases in the atmosphere and global warming, destabilize global and regional climatic conditions and, as a result, increase environmental stress to cultivated plants, ultimately altering conditions for their growth, development and crop bearing [3-6].

Annual cycle of plant growth and development may be organized into relatively distinct periods, which, in turn, could be favorable or unfavourable for cultivated plants. In particular:

- favorable winter period conditions will include no significant temperature changes, high snow cover, and optimal (for a particular plant variety) air humidity;
- unfavorable winter period conditions will include abrupt temperature changes, strong winds, deep thaws, absent or low snow cover;
- favorable spring period conditions - absence of significant temperature changes, optimal precipitation regime, rapid warming of the soil, absence of frosts (i.e. those that can cause damage to generative organs);
- unfavorable spring period conditions - a prolonged period of cold, large temperature ranges, precipitation extremes, frosts, periods of high solar activity and its rapid changes;
- favorable summer period conditions - temperature and precipitation regimes close to optimal, medium and low levels of solar activity;
- unfavorable summer period conditions - temperature and precipitation extremes, high solar activity;
• favorable fall period conditions - a smooth decrease in air temperature, and suboptimal precipitation regime;
• unfavorable fall period conditions - a sharp decrease in air temperature and precipitation, falling significantly out of the optimal conditions [7-9].

Analysis of meteorological observations and research results from previous years revealed that recurring severe winters (26 extremes during the last 140-year period) were the main limiting factor for the successful cultivation of fruit plants in the past. However, in recent years, winters have become significantly warmer (the average daily air temperature in December-February 2000-2017 was 11-18% higher than that in 1930-1960). Thus, at present this limiting factor has largely lost its relevance [7, 9].

Our previous research shows that more damage to the plant organism may be caused not exclusively by the sheer number of damaging factors, but rather by their particular combination and amplification of the impact. For instance, during long-term exposure of a plant to particular stress factors (extreme low or high air temperatures, soil waterlogging or drought, increased solar activity) the processes of photosynthesis and respiration substantially weaken, the activity of free radicals intensifies, and eventually all vital activity of the plant organism declines [9-11].

Thus, understanding of trends in the temperature and precipitation regimes in a region (including the East-European forest-steppe), identification of the main stressors to the cultivated plants, and the possible types of damage associated with particular negative factors are imperative for selection of the optimal areas of cultivation for fruit crops [11-13].

2. Materials and methods

Trends in the temperature and precipitation regimes for the last 20 years in the region of study were determined based on the climate archives of the Federal Service for Hydrometeorology and Environmental Monitoring of Russia (Roshydromet) for the Central Chernozem Region [7], and the interpolated meteorological data from the Monitoring Agricultural ResourceS (MARS) database of the Joint Research Centre, Institute for Environment and Sustainability archives (JRC-IES, European Union). For the latter, the decadal spatial interpolations with 25 km resolution from the European Centre for Medium-Range Weather Forecasts model (ECMWF, Reading, UK) were used for calculations and modeling [5, 7].

The reaction of fruit plants (Malus domestica, Pyrus communis L., Prunus cerasus L.) to various stressors was determined in orchards of fruit growing farms in the Tambov, Lipetsk, and Voronezh regions (Russia). Backlash against stress was evaluated during the whole year round, the frequency of sampling was: once every 2 weeks, after a stressor impact - once every 3 days. The plant functional response to various stressors was determined using the “Functional Diagnostic System for Fruit plant species” [8, 9]. The main assessment methods were: a histological test using the VIDEO-TEST morphology-4 complex (Carl Zeiss AG) with a freezing microtome, an integral assessment of the physiological state using the IFSR -2 instrument (fluorometric indicator of physiological status) and an infrared gas analyzer PP System Ciras-2.

3. Results and discussion

We analyzed the temperature and precipitation dynamics in the East European forest-steppe region in the last 85 years (1931 – 2017, all available data). Specifically, to adequately estimate temperature regime, precipitation regime, and potential heat and moisture accumulation, we investigated the dynamics of air temperature minima and maxima, dial temperature ranges, decadal ranges of growing degree-days (GDD), as well as decadal, annual, and monthly precipitation.

Mean annual air temperatures showed a minor rising tendency observed from 1997 year onwards. This slow rising tendency may possibly have a period over 100 years. However, the variance of the mean annual air temperatures substantially increased during the same period: first falling from 1.04 (variance units) in the period from 1931 to 1939 years, to the 1960 – 1969 minimum of 0.59 units, immediately followed by a steady growth towards the current (2011 to 2017 years) maximum of 8.4
units (Figure 1). Our analysis suggests a continuing increase in the mean annual air temperature range for the following decade(s), and a potential for further variability (possibly of a cyclic nature).

Further analysis of the annual air temperature minima and maxima also revealed a substantial change in the regional thermal regime, particularly during critical for fruit plants periods: (1) in October-November (preparation and transition of plants to a state of physiological rest), (2) in January-February (physiological rest, recovery from dormancy), and (3) at the end of April - the beginning of June (flowering, pollination, fruit development). We observed a significant increase in the dispersion of dial temperature ranges in October-November (1.1 units in 1960-1970 vs. 9.8 units in 2000-2014) and March-April (3.5 units in the period 1960-1970 vs. 14.7 units in 2000-2014).

![Dispersion of variance of the mean annual air temperatures in the East European forest-steppe region from 1931 to 2017.](image)

**Figure 1.** Dispersion of variance of the mean annual air temperatures in the East European forest-steppe region from 1931 to 2017.

We also discovered marked changes in the annual distribution of precipitation in the region of study. Particularly, in the period from 1960 to 1970 years most of precipitation (up to 70% of the annual total) fell from October to March, whereas in recent decades there has been a significant divergence in the timing, range and intensity of annual precipitation. Thus, we observed excessive humidification in June, September, as well as several periods of excessive precipitation in February-March; at the same time, the periods of increased aridity were observed in May, July, August, November and December (Figure 2).

Based on our analysis of the decadal precipitation patterns, we selected the period from 1960 to 1969 as the most climatically stable and favorable for the adequate growth and development of the cultivated fruit plants in the region of study. Consequently, the dataset for this period was chosen as a control dataset for further analysis of the current temperature and precipitation regimes in the region.

The growing instability of both temperature and precipitation regimes in the region during the last 40 years also affected the number, duration, and intensity of thaws in January - February. The average duration of thaws increased from 3 days (1960-1969 average) to 10 days (2000-2017 average). In the same period, the average maximum temperatures of thaws increased from 0.5 °C to 3.5 °C, while the daily temperature range, during the winter thaws, increased from a dial maximum of 9 °C in the 1960th, to up to 22 °C in the same period in the last decade.
In addition, since 1990, the years with temperature and precipitation extremes became more frequent, including a prominent drought in the year 2010. Matveyev [14], made a connection of the latter with a series of severe droughts in the European part of Russia ((1938) 1939 - (1971) 1972 - 2010), and found them roughly corresponding to the variations in solar activity, namely to the Brückner cycle (35-45 years harmonic of solar cycles) [15]. According to the above author [14], the relative amplitude and frequency of the natural cyclic sun-related fluctuations of climate have been altered by anthropogenic impacts, which led to initial amplification of certain harmonics, and may, potentially have directly influenced the intensity of the 2010 drought, i.e. through superposition of the concurrent minima in the 11-year cycle of solar activity ('sunspot cycle') and in its quasi-periodic (ca. 100-year) modulation (Gleissberg Cycle) [14].

Further, we argue that at present, the daily temperature range must be one of the key limiting factors for fruit plant species in the East European forest steppe region. Our analysis of the changes in air temperatures since 1931 showed that daily temperature ranges increased by a factor of three relative to the control period (the most climatically stable decade of 1960-1969, Figure 3). This type of instability causes a multifaceted damage to fruit plants.

Therefore, based on our analysis of the long-term (multi-decadal) climate variability and the associated response(s) of the fruit plant species, we established the key abiotic stressors for plant physiology in the Eastern European forest-steppe, and their effects on the cultivated fruit plant species in each growth period.
Figure 3. Dial air temperature ranges during the 2000 – 2017 period (blue line) and during the 1960 – 1969 period (the control set, red line).

These are:
- in the fall period:
  (1) a long period of higher than normal air temperatures in September-October with optimum humidity - extends vegetative growth period (causes revival of secondary vegetative processes), and significantly increases the risk of tissue damage during winter;
  (2) a sharp decrease of air temperature to low negative (in °C) values after a long period of warm weather, and in the absence of snow - leads to multiple damage to the cambial tissue and tissues of the root system;
- in the winter period:
  (1) long and deep thaws followed by a sharp drop in air temperature - disrupt key metabolic processes in fruit plants, and may incite anomalously early emergence of fruit plants from physiological rest; this requires excessive energy use and induces general weakening of plants and risks of tissue damage;
  (2) large diurnal air temperature ranges + high insolation levels, which cause so-called "sunburn" - the deep necrosis of long-term growth (including the cambial layer), and often lead to the die off of the annual growth (in some cases to the total loss of young plantations);
  (3) a sharp increase in air temperature, which induces active vegetative growth of the aerial part, while the root system remains dormant due to low soil temperature - results in excessive energy loss that risks limiting the growth and eventually the fruit crop yield;
- in the summer period:

(1) low air temperatures and high amount of precipitation, drought amid extremely high




temperatures; a consequential suppression of photosynthetic and enzymatic activity of


chlorophyll-containing tissues, necrosis of leaves and fruit tissues, complex weakening of


plants and increased risk of winter injury. A concomitant stressor is the associated activation


of pests and diseases amid the increased susceptibility of plants to them.


Effectively, all above periods are equally significant for plant growth and development, and the


physiological state of mature perennial plants is a result of a balance of positive and negative stimuli


throughout their lifecycle. However, long-term studies have shown that there are several most


vulnerable periods during the annual vegetative growth cycles of plants. These periods vary for


different cultivated plant species (Table 1).


Table 1. Periods of maximum risk of plant injury in cultivated plants.

| Plant variety | Growth period | Periods of max risk for plant injury | Phenological phase |
|---------------|---------------|-------------------------------------|--------------------|
| Fruit crops   | Crop bearing  | End of May - beginning of June       | Flowering, formation and growth of ovaries |
|               | Young         | Throughout the growing season        | All                |
| Shrubbery     | Crop bearing  | June - early July                    | Fruit ripening and active shoot growth |
|               | Young         | End of May – mid-June                | Active shoot growth |
| Herbaceous    | Annual        | End of June - beginning of July      | Flowering, seed formation |
| plants        |               |                                     |                    |

Analysis of data from the long-term monitoring of plants physiological state allowed to determine

the main types of injury to fruit plants observed in recent decades (Table 2).


Table 2. Types of injury to fruit plants observed in recent decades.

| At the organism level | At the tissue level | At the cellular level |
|-----------------------|---------------------|-----------------------|
| Vegetative and generative buds, annual shoots, forks of perennial branches, perennial branch, stem, whole plant | Corium, phloem, xylem, cambium, parenchyma, conductive tissue under vegetative and generative bud, rudiments of carpels, rudiments of stamens, cells of the tissue of the rudiment of the seed chamber, cells of the rudiments of leaves | Rupture of the cell wall, rupture of vacuoles, cell lysis, cell necrosis |

Different types of injury exhibit different levels of risk for fruit plants, both for the current crop and

for the plant itself, and, thus, are not equally dangerous for each of them. Here we rank different types

of injury according to the degree of risk to the crop and plants (Table 3).
Table 3. Types of tissue damage and their risk level for fruit plants.

| Type of damage                       | Injured organs on one plant (%) | Recovery capacity | Risk level for the current crop | Risk level for the plant |
|--------------------------------------|---------------------------------|-------------------|-------------------------------|---------------------------|
| Annual shoots                        | Up to 30% of branches           | Absent            | Low                           | Absent                    |
|                                      | Up to 80% of branches           | Absent            | Average                       |                           |
| Core of perennial branches           | Up to 30% of tissue             | High              | Low                           | Average                   |
|                                      | Up to 80% of tissue             | Low               | High                          | High                      |
| Wood of perennial branches           | Up to 30% of tissue             | High              | Low                           | Low                       |
|                                      | Up to 80% of tissue             | Low               | High                          | High                      |
| Cambium of perennial branches        | Up to 15% of tissue             | High              | Low                           | Low                       |
|                                      | Up to 50% of tissue             | Low               | High                          | High                      |
| Vegetative buds                     | Up to 40% of buds               | Mean              | Absent                        | Absent                    |
|                                      | Up to 70% of buds               | Low               | Average                       | Average                   |
| The transition zone under the vegetative bud | Up to 30% of tissue         | High              | Absent                        | Absent                    |
|                                      | Up to 70% of tissue             | Low               | Average                       | Weak                      |
| Flower buds                         | Up to 50% of buds               | High              | Low                           | Absent                    |
|                                      | Up to 90% of buds               | Low               | High                          |                           |
| The transition zone under the flower buds | Up to 30% of tissue         | High              | Low                           | Absent                    |
|                                      | Up to 70% of tissue             | Low               | High                          |                           |

It should be noted however, that regardless of the type of damage (i.e. tissue, organ) or the level of damage, any damage weakens the plant, reduces its protective potential, and, consequently, increases the risk of stress and injury.

4. Conclusions
Our study shows a persistently growing instability in the temperature and precipitation regimes of the East-European forest-steppe region, and this trend is expected to continue in the following years/decades. In particular have been increasing the frequency and amplitude of air temperature fluctuations, the number and intensity of thaws in January - February, while the timing, range and intensity of annual precipitation have been distorted, producing excessive humidity in June, September, some periods of February and March, and excessive aridity in some other months (May, July, August, November, December).

We determined the main types of frost injury of fruit plants at the level of cell, plant tissue and the whole organism. The ranking of the injury-risk levels for fruit plants, with relation to the type of damaged tissue and/or organ, showed that most dangerous for the fruit crops is the damage to generative buds and conductive tissues in the transition zone under the generative buds; for the whole plant, the greatest danger is an extensive (up to 80%) damage to the conductive tissues and cambial tissue. We have also determined that the most energy intensive and, therefore, most vulnerable phases of development of fruit plants are the periods of flowering and fruit formation. Synergistically, this leads to an increase in climatic stress for fruit plants and confirms the need to monitor and predict the risks of damage to fruit plants for timely and effective adjustment of the functional state of the plant.
organism. Therefore, the stress-specific adjustment of the current criteria for the selection of plant varieties for cultivation in the East-European forest-steppe region is required.

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