Variability in seasonal development of *Tilia cordata* in human-impacted areas

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Abstract. The article describes the results of long-term biomonitoring of habitat quality based on the phenology of the *Tilia cordata* tree species from the city of Yoshkar-Ola, Russia. Phenorhythms have been studied in trees of various ontogenetic states. The phenological observations took into account 13 phases of development of the vegetative and generative spheres of *T. cordata*. In urban conditions, the spring biorhythmological processes in *T. cordata* occur 3-10 days earlier than in natural conditions, while the autumn processes can begin even more significantly earlier, by 2-3 weeks. Its possible to distinguish age-related phenorhythmic groups with different rates of seasonal development in the studied local populations of *T. cordata*: 1 - with early onset and prolonged vegetation – trees of the generative period of ontogenesis of middle and old age, 2 - with late onset and rapid vegetation – trees of the generative period of ontogenesis of young age. In an anthropogenically transformed ecosystem, the individual rate of seasonal development of *T. cordata* can accelerate or slow down, which is more common for g2 and g3 ontogenetic states. Trends in the timing of the onset of phenophases at the research object in the forest park and in urban plantings in Yoshkar-Ola generally indicate the climate warming trend: earlier spring and later autumn dates are established, and the duration of the growing season is increasing. The multivariate phenorhythms of ontogenesis contribute to the growth of biodiversity and the adaptation of local populations of *T.cordata* to adverse environmental factors, including climatic stresses and pollution.

1 Introduction

The functioning of biological systems is realized in a space-time continuum. The rhythmicity of basic life processes, which is a universal property of living matter, can be observed at all levels of organization. Plant ontogenesis is directly influenced by seasonal climatic changes, which determine the seasonal nature of vegetation and plant growth [1, 2]. A characteristic feature of plant populations is their age heterogeneity [3, 4]. In modern classifications of multivariance of ontogenesis, rhythmic multivariance is singled out as one of the variants of dynamic multivariance. It is expressed in the mismatch of phenological states in individuals within the same cenopopulation [5].

One of the urgent tasks of modern phenology is the study of the influence of anthropogenic factors on the seasonal plant development. Despite the fact that changes in

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biorhythms are rarely used in bioindication practice due to the labor-intensive nature of the relevant methods, phenological parameters possess significant diagnostic potential. They are comprehensive in nature because they reflect the integrated response of an organism to changes in environmental conditions [6].

The temporal variability of various plant traits under conditions of air pollution remains an insufficiently studied area. Meanwhile, the reaction of embryophyts to atmospheric pollutants can vary significantly depending on the stage of ontogenesis [7, 8]. It should be noted that the specific conditions of the urbanized environment are a powerful factor determining the nature of the biorhythmic processes in plants [9].

Woody plants in cities are widely used for landscaping purposes. However, the range of plants should be selected based on their resistance to gaseous emissions from vehicles and industry. *Tilia cordata* Mill. is quite often used in urban landscaping. Sensitivity to atmospheric pollutants in *T. cordata* varies from low to high, according to various experts [8, 10].

The study of the temporal organization of populations and various manifestations of polyvariance in the ontogenesis of plant communities dominants in urban and suburban ecosystems is relevant for identifying sensitive species and labile traits of their individuals that best characterize the quality of the environment.

The aim of the study is to identify the lability of the rhythms of seasonal development of *T. cordata* in conditions of natural and anthropogenic disturbed ecosystems in order to determine the best bioindicators.

2 Materials and methods

Our work was carried out on the territory of Russia, the capital of the Republic of Mari El, the city of Yoshkar-Ola. Observations of the phenology of *T. cordata* began at the end of the last century, in 1999, when seasonal variability in the development of trees of this species was recorded for 3 years. After 25 years, studies of the phenorhythms of the model species were continued. The control observation area is the Pine Grove Protected Forest Park (ecotope 1). The trial sites were chosen based on a gradient of environmental pollution caused by motor vehicle emissions and industrial activity. Ecotope 2 was located in a residential area, which can be classified as a zone of low pollution. Ecotope 3 is one of the city parks. Ecotope 4 is a neighborhood of an pharmaceutical manufacturing facility.

Phenorhythms have been studied in *T. cordata* trees of various ontogenetic states – young, middle-aged, and old generative individuals [7]. Young generative individuals of *T. cordata* (g1) have an insular pyramidal crown. The lower part of the trunk is covered with a bark with deep cracks up to a height of 0.2-5 m. Middle-aged generative individuals of *T. cordata* (g2) have an acutely pyramidal, but more spreading crown. The trunk is cleared of lateral branches by 5-15 m, the bark is deeply cracked. The crown begins at a height of 3.5-8 m, its largest diameter is in the lower part. Old generative *T. cordata* individuals (g3) have a broad-pyramidal crown, which has almost lost its primary skeletal axes; they have been replaced by branches that arose from dormant buds (secondary crown). The upper lateral branches are flush with the main axis, which has almost stopped growing.

240 trees were observed. In 2024, we observed only trees at the peak of ontogenesis – middle-aged generative trees. Phenological studies were carried out according to standard traditional protocols: in spring – often, every 2 days, in summer and autumn – once a week. 13 phases of development of vegetative and generative organs of T. cordata were recorded during the growing season. The following phases of the development of vegetative organs were noted: resting state of the kidneys, swelling of the buds, budbreak, the beginning of leaf unfolding, leaf unfolding, completion of leaf growth, discoloration of the leaves, leaf fall. The following phases of the development of generative structures of T. cordata were

observed: resting state of male inflorescences, swelling of inflorescences, bud formation, beginning of flowering, mass flowering, end of flowering, fruit ripening [6, 11, 12].

The authors carried out statistical processing of the results using the Statistica 13 program using the MANOVA methods (model I), Scheffe test, criterion $\chi 2$ [13].

3 Results and discussion

The phenological development of *T. cordata* in a temperate climate zone occurs from spring to autumn, with a winter diapause. The beginning of the growing season occurs after the snow has melted, and the end occurs after the leaves have fallen. The vegetation of the nemoral *T. cordata* species begins later and ends earlier than that of boreal species in the coniferous-broadleaf forest subzone.

The beginning of the growing season in *T. cordata* is recorded by the swelling of the buds; in the subzone of coniferous-deciduous forests, this usually occurs in late April – early May. For example, let's describe the spring phases of the development of vegetative organs. The resting state of the buds was noted if there were no external signs of bud growth. Swelling of the buds: the size of the buds is increased, light stripes appear from under the opened covering scales. If the tops of real leaves appear in the buds between the expanded scales, the phenophase of budding was recorded. The beginning of the unfolding of leaves is recorded when the folded leaves come out of the buds halfway. The full unfolding recorded when the leaves are fully open.

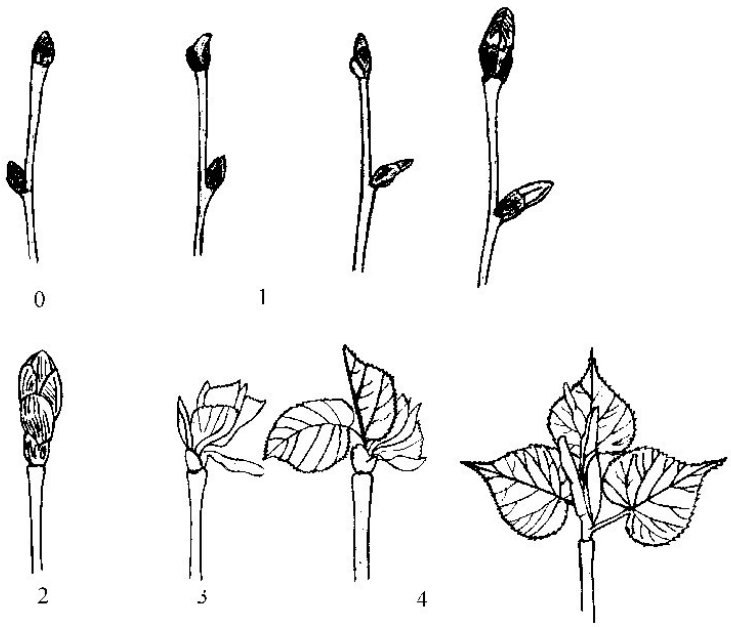

Fig. 1. Spring phases of development of vegetative organs of *T. cordata*: 0 – resting state of the buds, 1 – swelling of the buds, 2 – bud formation, 3 – beginning of leaf unfolding, 4 – full leaf unfolding

During the first cycle of observations of *T. cordata* phenorhythms and 20 years later, the asynchrony of the onset of phenophases in natural and transformed ecosystems was revealed. In urban conditions, the spring biorhythmological processes in T. cordata occur 3-10 days earlier than in natural conditions, while the autumn processes can begin even more significantly earlier, by 2-3 weeks (Table 1).

Table 1. An increase in the timing of the onset of vegetation (in days) for *T. cordata* in an urban environment compared with a suburban forest park

Phenophase		Ecotope 2			Ecotope 3			Ecotope 4		
		1999	2001	2024	1999	2001	2024	1999	2001	2024
Start of the growing season		0	+7	+4	+7	+7	+6	0	+7	+7
Leaf unfolding	start	0	0	+4	+6	0	+6	0	0	+7
	end	0	0	0	+7	0	+6	+7	0	+4
Flowering	start	+4	0	+4	+4	+3	+6	+6	+9	+7
	end	0	0	0	0	+4	+3	0	+4	+4
Leaf yellowing	start	+7	0	0	+7	+7	+14	+21	+21	+7
	end	0	0	+6	0	+6	+6	+6	+6	0
Leaf fall	start	+7	0	0	+7	+7	+14	+21	+21	+7
	end	0	0	+7	0	+7	+7	+7	+7	0

This acceleration of the rhythms of urban tree development is easily explained by the warmer microclimate of ecotopes. Such a background and local temperature increase occurs due to the proximity of tree plantings to asphalt pavement and buildings that will accumulate and then release heat. The general background of elevated temperatures in the city is added by the ingredient pollution. In addition, do not forget about artificial lighting, which contributes to the acceleration of plant phenorhythms in cities. Table 1 shows that shifts in the seasonal development of *T. cordata* is more significant in autumn compared to spring. There is an acceleration in the spring processes of leaf blooming in the urban environment for *T. cordata* individuals. The flowering of urban linden trees may begin earlier, but it stretches over time, compared to trees in the suburbs. However, it is worth noting that our observations sometimes recorded a later onset and reduction of flowering. This can be explained by differences in weather conditions between different years of observations. The accumulation of pollutants in the leaves most likely leads to premature defoliation, which is observed in *T. cordata* individuals in industrial and transport areas of the city. In urban conditions, the duration of yellowing and leaf fall is longer than in natural conditions. Perhaps this is due to the presence of artificial street lighting and the higher air temperature in the city. There was also a significant decrease in life activity and vegetation ($P < 0.01$-0.05).

There is an acceleration in the rate of development of *Tilia* L individuals in other cities as well. In central-eastern Poland, scientists have noted an acceleration in the development of generative organs in *T. americana*, *T. cordata*, *T.* × *euchlora*, *T. platyphyllos*, and *T. tomentosa* [14]. In other studies, using the example of European cities, the significant contribution of artificial lighting to the acceleration of the phenorhythmology of tree species has been shown [20]. For *Betula pendula* Roth – in the European Russia center, there has been a general trend towards a later time of leaf yellowing and leaf fall. This phenomenon may indicate a shift in the growing season to an earlier date [15]. We found similar patterns in our study too.

In addition to exogenous factors, the rate of phenophase in *T. cordata* is significantly influenced by endogenous features, in particular, biological age. Our research has revealed asynchronous phenorhythmics in trees of different ages. It was found that in conditions of environmental pollution, the duration of leaf unfolding is reduced in middle-aged and old generative individuals, but the duration of flowering increases. At the same time, with an increase in the biological age of plants, the duration of yellowing of foliage and leaf fall increases. In the zone of moderate pollution (ecotope 4), the longest leaf life is typical for individuals at the peak of ontogenesis. Thus, two age-related phenorhythmic groups can be distinguished in the studied populations of *T. cordata*: early and long-term vegetative (middle-aged and old generative individuals) and late, short-term vegetative (young generative individuals).

Seasonal development is also determined by individual characteristics. At the initial stages of the study, it was found that within the age-related phenorhythmic groups there are individuals with different rates of development: normal, accelerated and delayed. This leads to variations in the total duration of vegetation, as well as shifts in the timing and duration of individual phenophases. In relatively clean conditions, individuals with an average rate of development dominated in all groups. Under conditions of industrial and transport pollution, the proportion of trees with accelerated and delayed development significantly increased in the middle-aged and old generative groups ($P<0.01–0.05$). In 2024, in the middle-aged group, under conditions of moderate pollution, there was a pronounced variability in the rate of seasonal development. Acceleration or deceleration of development is probably a mechanism for maintaining population resistance to adverse weather conditions and atmospheric pollution, since under such stresses (frosts, emissions), some individuals at different stages of development are less damaged.

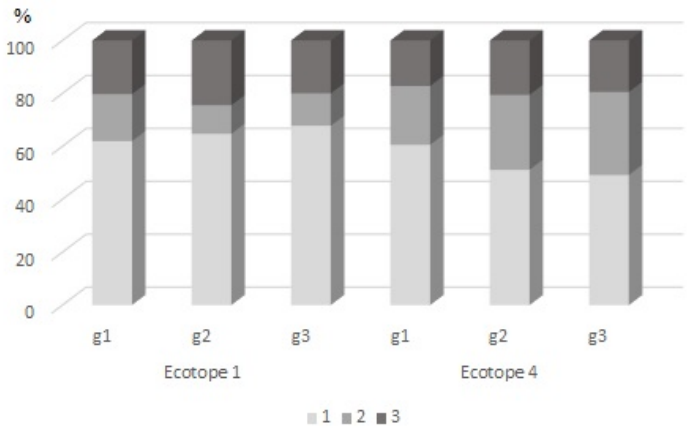

Fig. 2. The proportion of *T. cordata* individuals belonging to different ontogenetic groups based on their seasonal development: 1 – typical, 2 – advanced, 3 – delayed.

An increase in the degree of heterogeneity of local *T. cordata* populations is associated with the asynchrony of phenological development at the individual and group levels. The individual rate of seasonal development is the result of both phenotypic and genotypic variability. Most likely, we observed a wide norm of morphogenesis of vegetative and generative organs of *T. cordata*. It is thanks to this that trees can quickly adapt to fluctuations in the weather conditions of a particular growing season. On the other hand, the annual acceleration or deceleration of development in some individuals suggests, most likely, a genotypic basis for the phenorhythmotype. With global changes in climate processes, directional selection can contribute to the survival of such individuals with altered rhythms of seasonal development.

4 Conclusions

The dynamics of the seasonal development of the studied species is influenced by a complex of exogenous (weather conditions, pollution) and endogenous (age and individual characteristics) factors. In an anthropogenically altered environment, there is a multivariance of the ways of seasonal development of *Tilia cordata*. The rhythmological multivariance of *T. cordata* is manifested in individuals, ontogenetic groups, and local populations in various urban environments and by year. Although the timing of the onset of phenophases and their

duration are determined by the weather conditions of a particular growing season, the general pattern in the passage of phenophases by trees of different biological ages in various environmental conditions in Yoshkar-Ola remains stable. Trends in the timing of the onset of phenophases at the research object in the forest park and in urban plantings in Yoshkar-Ola generally indicate the climate warming trend: earlier spring and later autumn dates are established, and the duration of the growing season is increasing. The rhythmological multivariance of ontogenesis increases the degree of biodiversity of local populations of *T. cordata* and contributes to their adaptation to adverse climatic factors and environmental pollution.

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