Modeling the productivity of intensive and super-intensive apple orchards in the midland of Russia

Yu V Trunov, A V Solovyev, A A Zavrazhnov, Z N Tarova

Michurinsk State Agrarian University, 101, International st., Michurinsk, 393760, Russia

E-mail: trunov@mgau.ru

Abstract. It is known that the main trend in the development of modern world gardening is the creation of intensive and super-intensive gardens, and the degree of intensity of the garden increases with an increase in the number of trees per unit area (compaction of tree layout). The paper considers the patterns of productivity of intensive apple orchards during the reproductive cycle depending on tree planting density. The paper presents the models of apple tree productivity in intensive and super-intensive orchards representing regression equations approximated by polynomials of 2 and 3 degree with determination coefficients $R^2 = 0.97-0.99$. According to the above models, a total yield of up to 516 ton/ha may be obtained in an intensive garden with a tree planting density of up to 1500 wood/ha for 18 years of commercial fruiting, a total yield of up to 790 ton/ha may be obtained in a super-intensive garden with a planting density of more than 9,500 wood/ha for 16 years of commercial fruiting (an increase in the total productivity of planted vegetation of more than 1.5 times). The models (dependencies) of development of industrial apple orchards of different planting scheme are obtained, approximated by sigmoidal logistic functions defining three stages of logistic yield growth at the beginning of garden development (“growing up”), having exponential, linear and hyperbolic nature respectively. Logistics trends of the relative yield of the garden and the relative productivity of trees were established, according to which an increase in the yield of industrial gardens due to an increase in planting density is accompanied by a decrease in the productivity of fruit trees.

1. Introduction
The main trend in the development of modern world gardening is the creation of intensive and super-intensive gardens. In the modern sense, the degree of intensity of the garden increases with an increase in the number of trees per unit area (compaction of tree layout). Conditionally, a garden is considered intensive with a tree planting density from 1400-1500 to 2500 wood/ha, super-intensive – more than 2500 wood/ha. The most common tree layout schemes in the world in super-intensive apple orchards on small-stature form of stock – 3.0-4.0×0.7-1.0 m (2500-4760 wood/ha) [1, 2, 3].

In Russia, at the present stage, gardening is undergoing a difficult period due to both objective and subjective reasons [4], in particular:

- unfavorable natural and climatic conditions in a vast territory of Russia and the ability of perennial plants to accumulate negative consequences of stressors;
- obsolete and very worn out material and technical base of most previous horticultural farms;
- outdated technologies for cultivating existing perennial plantations.
The main task of compacting intensive plantations is to increase productivity per unit area, accelerate commercial fruiting, improve cost/benefit justification, and reduce the cost of production [5].

The purpose of the study is the economic and biological assessment of intensive apple plantations in orchards of various density, including super-high, and the construction of productivity models of intensive and super-intensive orchards.

2. Materials and methods
The study was carried out for 30 years (1990-2020) in the best specialized horticultural farms in the midland of Russia: CJSC Agrofirma named after 15 years of October, OJSC Agronom (Agronom-Garden LLC) of Lipetsk Region, JSC Dubovoye, JSC Komsomolets Uchkhoz-Plemzavod of Tambov Region, LLC Krasinskoe, LLC Don Gardens of Voronezh Region, LLC Veidelevskoye of Belgorod Region, etc.

An intensive apple orchard was laid in Tambov Region, at Michurinsk State Agrarian University in the spring of 2019 on a highly winter-resistant medium-grown stock 54-118 of Professor V.I. Budagovsky selection (Michurinsk SAU) with a tree planting density of 4.0×1.5 m (1667 wood/ha). Varieties – Ligol and common Antonovka.

54-118 – medium-grown stock characterized by high frost resistance of the root system [6].

A super-intensive apple orchard was laid in the spring of 2020 on high winter-resistant small-stature form of stock of Paradizsk Budagovsky (V9) of Professor V.I. Budagovsky selection (Michurinsk SAU) with very high tree planting density: 1.5×0.7 m (9524 wood/ha). Varieties – Lobo and Honey Crisp.

Paradizka Budagovskogo stock – small-stature form of stock in terms of growth strength close to M9 is characterized by frost resistance high enough for midland conditions [6].

Soils – heavy loamy leached chernozems, medium-sized, slightly acidic, medium-rich with the main elements of mineral nutrition.

The plants took root well and in the first year after planting gave a yield of 2.0-2.5 t/ha of high-quality fruits (Fig. 1).

![Figure 1](image.png)

**Figure 1.** Fruiting of the apple tree in a super-intensive garden on a small-stature form of stock Paradizsk Budagovsky planted in 2020, with a layout of 1.5×0.7 m (9524 wood/ha), in the first year after planting. Varieties: 1 – Lobo; 2 – Honey Crisp.

3. Results and discussion
The analysis of statistical data and predictive studies allowed carrying out mathematical modeling of development and yield of industrial apple orchards of intensive and super-intensive type during their life cycle [4, 7-13].
The modeling was carried out within the following limitations and assumptions:
- Data for planting schemes (planting densities): 4.5×1.5 (1481 wood/ha); 4.0×1.0 (2500 wood/ha); 3.0×1.0 (3333 wood/ha); 1.5×0.7 (9524 wood/ha).
- All planting schemes use the same type of cultivation technology.
- Periods of commercial fruiting are taken from the yield level of more than 10 t/ha.
- Periods of stable (greatest) fruiting are accepted more than 85% of the maximum possible.

The simulation results are presented in Table 1, which defines the yield matrix with the life cycles of planted vegetation.

| Stock        | 54-118. | 62-396  | PB (V9). | PB (V9). |
|--------------|---------|---------|----------|----------|
|              | 62-396  | P60     | M9       | M9       |
| Planting scheme, m | 4.5×1.5 | 4.0×1.0 | 3.0×1.0  | 1.5×0.7  |
| Density, wood/ha | 1481    | 2500    | 3333     | 9524     |
| Garden time frame | 25      | 22      | 20       | 18       |
| Fruiting years | 23      | 21      | 20       | 18       |
| Years of commercial fruiting | 18      | 18      | 18       | 16       |

Table 1. Yield matrix of industrial apple orchards of intensive and super-intensive type
Figure 2 shows the yield of intensive and super-intensive industrial apple orchards over their life cycle.

The approximation of diagrams presented in Figure 2 with polynomials of 2 and 3 degree allowed obtaining the regression models of development and yield. The approximation was carried out taking into account the accepted limitations and according to standard Excel notes (programs).

Figure 2. Yield diagrams of industrial apple orchards of intensive and super-intensive type.

Figure 3 and Table 2 show the approximated dependencies (regression models), the type of models and the assessment of their adequacy (validity) by the determination coefficient.

Table 2. Dependencies of development and yield of industrial apple orchards of intensive and super-intensive type

| n/n | Dependence (models) | Regression model | Model adequacy assessment |
|-----|---------------------|------------------|---------------------------|
| 1   | S 4.5×1.5           | $y = -0.0621x^3 + 1.2239x^2 - 2.9112x + 1.7636$ | $R^2 = 0.9987$ |
| 2   | S 4.0×1.0           | $y = -0.0805x^3 + 1.3389x^2 - 0.8428x + 1.6133$ | $R^2 = 0.9926$ |
| 3   | S 3.0×1.0           | $y = -0.1525x^3 + 2.1391x^2 - 1.0371x + 3.2476$ | $R^2 = 0.9944$ |
| 4   | S 1.5×0.7           | $y = -0.2399x^3 + 2.6732x^2 - 1.7942x + 4.1357$ | $R^2 = 0.9984$ |
| 5   | Sn                  | $y = 0.377x^2 - 18.236x + 235.17$ | $R^2 = 0.9661$ |
| 6   | So                  | $y = 0.825x^2 - 24.619x + 199.45$ | $R^2 = 0.9908$ |
The dependencies indicated in Figure 3 as $S_{4.5\times1.5}$; $S_{4.0\times1.0}$; $S_{3.0\times1.0}$; $S_{1.5\times0.7}$ represent the development models of industrial apple orchards of various planting patterns.

The dependencies indicated in Figure 2 as $S_u$ and $S_o$ distinguish zones of stable and highest yield of these gardens.

The visual evaluation of the regression models $S_{4.5\times1.5}$; $S_{4.0\times1.0}$; $S_{3.0\times1.0}$; $S_{1.5\times0.7}$ and the high degree of their adequacy allows attributing these models to a family of the so-called sigmoidal functions, which are mathematical functions that have the characteristic of an S-curve and which are used to describe and study dynamically developing processes in various areas of science and practice.

A typical example of a sigmoidal function is the classic Verhulst growth logistic function, which in our case has the following form:

$$\frac{dY}{dT} = kY\left(1 - \frac{Y}{L}\right)$$  \hspace{1cm} (1)

where $Y$ – yield; $L$ – maximum marginal yield for a particular type of garden; $T$ – time (years); $k$ – coefficient determining the yield increase.

Figure 4 shows a typical diagram of function (1) defining three stages of logistic yield growth during garden development (“growing up”).

The Verhulst function, like most other logistical laws, defines three main stages of development, with hard-to-see transformation points (inflection points) of dependency:

• Stage I – period of slow growth (development), mainly having an exponential character;
• Stage II – period of growth (development), having an almost linear character;
• Stage III – period of retarding growth (development), having a hyperbolic character and striving for a certain level of saturation $L$ (in our case – the maximum marginal yield for a particular type of garden).

A distinctive feature of the logistic growth function is the ability to estimate the quality (intensity) of the dynamic process by comparing the values of the $K$ coefficient (determining the slope of the function in the main growth section) and the saturation value $L$.

It is clear that in the case of estimating the quality (intensity) of industrial gardens with different patterns and planting densities, the increased $K$ and $L$ values characterize faster entry into commercial fruiting and higher yields (Figure 2).
However, the analysis of the discrete analogue of the continuous function (1) revealed additional points of assessment of industrial gardens.

Let us consider the yield of a certain type of garden at successive points in time (years). The yield dependence at time interval $T + 1$ on the yield in the previous interval $T$ may be written as follows:

$$Y_{T+1} = \int(Y_T, k, P)$$  \hspace{1cm} (2)

where $Y_T$ – yield of the previous year; $Y_{T+1}$ – productivity of the next year; $P$ – productivity of an individual fruit tree for a specific type of garden; $k$ – coefficient determining the yield increase.

The introduction of the productivity parameter ($P$) into equation (2) turns the Verhulst equation (1) into a special case of a feedback process (shown in Figure 5) in which the same fruiting process is consistently repeated.

$$Y_{T+1} = f(Y_T, k, P)$$

The solution of the dependence (2) in accordance with the structural scheme is possible using the garden yield and fruit tree productivity, presented in relative form.

A matrix of the relative yield of plantations and the relative productivity of trees in orchards of various types during the period of commercial fruiting is compiled based on Table 1.
Table 3. Matrix of yield and productivity of industrial apple orchards with different planting density during commercial fruiting

| Planting density | Average yield of a garden during commercial fruiting | Average fruit tree productivity | Relative yield of the garden | Relative productivity of trees |
|------------------|------------------------------------------------------|-------------------------------|-----------------------------|-------------------------------|
| wood/ha          | t/ha                                                 | kg/wood                       | \( \frac{O_{9524}}{O_{1481}} \) | \( \frac{I_{1481}}{I_{9524}} \) |
| 1481             | 26.8                                                 | 18.1                          | 0.55                        | 1.00                          |
| 2500             | 33.0                                                 | 13.2                          | 0.68                        | 0.73                          |
| 3333             | 38.0                                                 | 11.4                          | 0.78                        | 0.63                          |
| 9524             | 48.8                                                 | 5.1                           | 1.00                        | 0.28                          |

The calculation and approximation of obtained dependencies by power functions are shown in Figure 6.

![Figure 6](image)

**Figure 6.** Logistics trends of relative yield \( S_Y \) and productivity \( S_p \) for industrial apple orchards with different planting densities.

The logistic trend of relative yield is characterized by power regression dependence of the following type:

\[
Y = 0.0564 X^{0.32} \quad (R^2 = 0.9727). \tag{3}
\]

The logistic trend of relative productivity is characterized by a power regression dependence of the following type:

\[
Y = 155.36 X^{-0.68} \quad (R^2 = 0.9938). \tag{4}
\]

The obtained dependencies make it possible to conclude that the increase in the yield of industrial orchards due to the increase in planting density is accompanied by a decrease in the productivity of fruit trees. Moreover, this relationship is quite close, since the sum of the absolute values of the degree indicators in dependencies (3, 4) is 0.32+0.68=1. This conclusion should be taken into account when
designing intensive and super-intensive industrial gardens.

4. Conclusion
The paper presents the models of apple tree productivity in intensive and super-intensive orchards representing regression equations approximated by polynomials of 2 and 3 degree with determination coefficients $R^2 = 0.97-0.99$. According to the above models, a total yield of up to 516 ton/ha may be obtained in an intensive garden with a tree planting density of up to 1500 wood/ha for 18 years of commercial fruiting, a total yield of up to 790 ton/ha may be obtained in a super-intensive garden with a planting density of more than 9,500 wood/ha for 16 years of commercial fruiting (an increase in the total productivity of planted vegetation of more than 1.5 times).

The models (dependencies) of development of industrial apple orchards of different planting scheme are obtained, approximated by sigmoidal logistic functions defining three stages of logistic yield growth at the beginning of garden development (“growing up”), having exponential, linear and hyperbolic nature respectively.

Logistics trends of the relative yield of the garden and the relative productivity of trees were established, according to which an increase in the yield of industrial gardens due to an increase in planting density is accompanied by a decrease in the productivity of fruit trees.

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