DOI: https://doi.org/10.21323/2618-9771-2023-6-4-504-511

Received 17.07.2023
Accepted in revised 28.11.2023
Accepted for publication 01.12.2023

Available online at https://www.fsjour.com/jour
Review article
Open access

THE ECOSYSTEM OF VERTICAL FARMS: A CONCEPTUAL FRAMEWORK

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KEY WORDS:
vertical farms, agro-industrial complex, digital technologies

ABSTRACT
The article discusses the prospects of creating vertical farms as a modern eco-friendly solution to increase the productivity of the agro-industrial complex. Throughout the work, the authors justify the need to switch from the old model of food security to a new one, which is based on innovative agricultural technologies. In particular, the nature of vertical farms, their organization models, as well as their relevance for the "smart city" concept are considered. The paper discusses the ecosystem of vertical farms and the role of various stakeholders. The importance of vertical farms for digital transformation of agriculture is demonstrated.

Поступила 17.07.2023
Поступила после рецензирования 28.11.2023
Принята в печать 01.12.2023

https://www.fsjour.com/jour
Обзорная статья
Open access

ЭКОСИСТЕМА ВЕРТИКАЛЬНЫХ ФЕРМ: КОНЦЕПТУАЛЬНАЯ ОСНОВА

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КЛЮЧЕВЫЕ СЛОВА:
вертикальные фермы, агропромышленный комплекс, цифровые технологии

АННОТАЦИЯ
В статье рассматриваются перспективы создания вертикальных ферм как современного экологичного способа повышения производительности агропромышленного комплекса. В работе авторы обосновывают необходимость перехода от старой модели продовольственной безопасности к новой модели, основанной на инновационных агротехнологиях. В частности, рассмотрены сущность вертикальных ферм, модели их организации, а также их соответствие концепции «умного города». В статье обсуждается экосистема вертикальных ферм и роль различных заинтересованных сторон. Показана важность вертикальных ферм для цифровой трансформации сельского хозяйства.

1. Introduction

While the existing models of agricultural production that emerged after the first Green Revolution [1,2] have demonstrated a high level of efficiency due to application of advanced biotechnologies, digital technologies, innovative models of management and international division of labor, their ability to ensure sustainable and resilient food security for the global population in the present economic, social, and geopolitical situation is still under question:

- Food supply chains include companies from many countries and depend on unhindered movement of goods between these countries. However, the recent events (pandemics of COVID-19 [3], special military operation in Ukraine [4] etc) demonstrated that these food supply chains have a low level of resilience against those shocks and may not be able to provide people with sustainable access to food in case of crisis [5] (as was shown by rationing of basic foods in Europe during pandemics customers' rush [6]).
- People are interested in replacing (or complementing) the global food supply chains by alternative food networks that connect the local producers and the local customers [7]. This interest is supported by customers' willingness to support local agriculture, to improve the quality of food they buy and to get access to food that is absent in food retail chains (including food that corresponds to changing values of customers) [8,9,10];
- The world population keeps growing, as a result, the area of agricultural land per person decreases [11,12]. For this reason, to ensure food security it is necessary to use the limited land resources as efficiently as possible [5,12,13];
- The existing models of agricultural production create a pressure on environment thus leading to its pollution [14,15,16], land degradation [17], risks for biodiversity [18] etc. Moreover, the models of food chains management have a negative social impact (dispossession of farmers [19], destruction of rural environment [20], demographic shifts [21] that cannot be neglected. Taking into account the growing importance of ecological and social values for the customers (and for the society in general) these negative effects lead to a demand for innovative models of food production and management of food systems [22].

It means that global food supply chains should be complemented and partially replaced by the alternative models of food production and distribution that would contribute to both higher productivity of land resources [11] (due to innovative technological solutions including precision agriculture [23], smart agriculture [24,25], introduction of new edible resources (insects etc. [26,27]), cultured meat [28,29,30] and cellular agriculture [31], genome engineering [24] etc.) and higher resilience of food chains (achieved by reducing the distance between the producers and the consumers in order to reduce the risks of food supply chains shocks [32,33,34]). Special attention should be paid to local food systems, as in addition to a higher resilience they can provide local customers with guaranteed access to locally grown high quality fresh food [34]. Sustainability of new food chains is also an important requirement as people's awareness of ecological values is constantly growing [8,10,35].

One of the ways to reach these goals can be introduction of so called, urban agriculture that can be described as agricultural production situated within the cities and peri-urban areas [36,37,38]. While urban agriculture is a centuries-old practice, it has traditionally been limited to individual producers who grew vegetables, poultry etc. at home [39] or on the small land plots provided by the city authorities [40]. This model of urban agriculture (in general being the form of subsistence agriculture) is oriented towards the consumption of the products by the growers [41,42]. However, thanks to technological, social and organizational development the new forms of urban agriculture emerge (community gardens [43,44], urban farms [45], rooftop farming etc. [46]) that help overcome inefficiencies of traditional agriculture [45], increase resilience and outreach of food security systems (by eliminating food deserts [47], thus providing people in need with affordable food [48,49], protecting food supply chains against shocks [50]) and create positive social and ecological effects [23,51,52]. One of these forms is the vertical farms [53,54,55].

Vertical farms, which are often called as urban farms or indoor farms [56], are the agro-industrial facilities in the cities and peri-urban areas consisting of vertically arranged tiers of certain substrate assigned for

FOR CITATION: **Dovganeva, Y. A., Katrashova, Y. V., Kirillova, T. V.** (2023). The ecosystem of vertical farms: A conceptual framework. *Food systems,* 6(4), 504-511. https://doi.org/10.21323/2618-9771 2023-6-4-504-511

ДЛЯ ЦИТИРОВАНИЯ: **Довганёва, Ю. А., Катрашова, Ю. В., Кириллова, Т. В.** (2023). Экосистема вертикальных ферм: концептуальная основа. *Пищевые системы*, 6(4), 504-511. https://doi.org/10.21323/2618-97712023-6-4-504-511

growing plants and (or) animals (mainly mariculture, however, there are also the urban farms for other species) [54,55,57]. This model of organization of agricultural production supports the idea of intensive use of space as due to this method the minimal space gives high yield productivity and helps maintain an optimal microclimate [11,12,55]. Vertical farms represent a new stage of development of urban agriculture as they are based on large and highly automated agro-industrial facilities located within the cities [58,59]. High intensity of space usage is based on hydroponic and aeroponic technologies [12,55,60].

Currently, there is a significant number of publications on the vertical farms that can be divided into the following research streams [63,64,65]:

Technological aspects of the vertical agriculture [12,55,59]. The goal of this research stream is to determine key technologies that can be used for vertical agriculture and to evaluate their advantages and disadvantages [56,60]. It is important to highlight that despite the growing popularity of vertical farms, the scientists raise concerns about their real efficiency as the technologies of vertical farming may be still immature [61] and the energy consumption is high [62];

Role of vertical agriculture for urban food security [53,63,64]. As the current level of geopolitical, ecological, climatic, economic and social risks is very high, it is extremely important to ensure resilience of food supplies to the cities;

Organizational and economic tools that can be used in order to ensure efficiency of vertical farms [65]. Being innovative players on agricultural market, urban farms may be associated with higher risks in comparison with the traditional agricultural businesses [65]. Finding the ways to ensure their efficiency and selection of tools of elimination of risks is crucial for development of vertical agriculture;

Environmental effects of the urban farms [66,67]. Ecological values play an important role for modern society as they comprise a part of ESG-transformation [8,10]. Innovative models of agriculture have to comply with these values.

Nevertheless, two issues remain relatively poorly studied:

- the system of relations between the participants of the ecosystem of vertical agriculture. Expansion of the vertical agriculture means that new stakeholders in agricultural industry emerge, and the system of relations between the existing stakeholders and the new stakeholders is constantly changing. Understanding these changes is essential in order to implement the state and corporate strategies of development of the vertical agriculture as a new element of urban food security. However, despite the popularity of ecosystem approach for analysis of companies, industries and markets, the literature on vertical farms does not consider this approach. The study of linkages between the vertical farms and external actors usually includes only cooperation between the operators of vertical farms and technology providers [56]. Obviously, it is possible to provide conditions for the development of the vertical agriculture only on the basis of understanding of the goals and the conflicts of stakeholders of the vertical farms ecosystem;
- the role of vertical farms in digital transformation of agriculture [25,68]. While vertical farms strongly depend on digital technologies, these technologies are only analyzed as a technological basis of the vertical farms [12,55,59]. However, being an innovative form of agricultural production, the vertical farms can also contribute to digital transformation of agriculture [68,69]. Moreover, as vertical farms are situated within the cities and peri-urban areas they can be considered as a tool of social transition towards smart cities [70,71,72]. This aspect is extremely important as putting vertical farms in the context of the digital transformation of global economy will help increasing efficiency of the vertical farms by linking them to the other digital systems.

The present paper represents an attempt at filling in these gaps. The goal of the research is twofold:

- Identification of the composition of the vertical agriculture ecosystem and the description of interests, goals and conflicts of its stakeholders.
- Analysis of the role of vertical farms in the digital transformation of economy.

The contribution of the present research to the existing literature on vertical agriculture is made up of identification of potential models of pooling resources of various stakeholders to promote the vertical farms as an innovative model of agricultural production.

2. Objects and methods

The present research is based on ecosystem approach. The concept of ecosystems as a model of organization of business activities was introduced by Moore [73]. Ecosystems exist at the project, in the corporate and industrial level, and can be broadly defined as the open networks of various stakeholders that have common and private interests and who influence the development of this project (business, industry etc.). The balance of the common and private interests of various groups of stakeholders leads to a coopetition among them.

Concept of ecosystems has been successfully applied to analysis of various economic objects (platforms [74], fintech [75], cryptocurrencies [76], cities [77] and helped to understand the structure of stakeholders concerned in these objects, the nature of their relations as well as their impact on the development of these objects [78]. It means that ecosystem approach is a powerful research methodology and can be applied to analysis of vertical farms industry.

Stakeholders are the groups of economic agents with more or less uniform interests, goals and models of participation in economic activities (and similar model of interaction with the economic object under analysis).

In order to identify the specific groups of stakeholders in the vertical agriculture we use the general method of analysis and synthesis. For description of the impact of the vertical farms on digital transformation of agriculture we use the method of strategic matrices [79].

3. Results and discussion

3.1. Advantages of the vertical farms

Vertical farms feature many advantages in comparison with traditional agriculture:

- More efficient use of limited land resources due to vertical arrangement of production facilities, as vertical farms are multi-floor buildings [12]).
- Vertical farms are less dependent on climatic conditions [80] because of internal microclimate supported by special technological equipment [60]. Thanks to independence from climatic conditions the vertical farms can be used for organization of agricultural production in area where traditional agriculture is impossible [81,82]. These measures will ensure food security of these areas. It also helps increase efficiency as multiple production cycles can take place all year round. Finally, it helps to reduce the negative effects of climate change [80,83].
- Better food supply for the cities [53,54,84]. Vertical farms can be located within the urban areas thus eliminating the distance between the place of production of food and the place of its consumption which makes food supplies more resilient.
- Shorter food supply chains of retail operators and lower logistic costs for retail chains.
- Lower environmental damage (less fertilizers, lower water consumption, less fuel for transportation, no deforestation) [54]. However, according to Vaughan [85], ecological effects of vertical agriculture are unclear.
- Promotion of organic consumption.
- Rehabilitation of urban landscape. Since the cities have a large number of abandoned buildings and territories (due to deindustrialization), it is possible to consider these resources as a place to create vertical farms, which will improve the quality of the urban environment.

Development of the vertical farms corresponds to main trends of evolution of agriculture:

- Expansion of green agriculture (that is more environment friendly than the existing model of agricultural production). Ecological values become more important for customers [8,86]. In the same time the legal pressure on business that do not care about the environment is constantly getting harder. Producers of food have to comply with these requirements and development of vertical agriculture is a good option.
- Urban agriculture which encompasses various forms of growing food in cities organized by companies, communities and individuals (like urban gardening). Urban agriculture helps to improve the quality of food and to increase the efficiency of use of city lands.
- Smart agriculture as vertical farms are very much dependent on digital technologies that control and optimize all processes.

It means that in addition to being an innovative model of ensuring food security the vertical agriculture plays a strong transformative role for the customers, food producers and cities as it promotes new models of land use, production of food and interactions within the framework of food consumption.

3.2. Vertical farms as a tool for the development of the smart city concept

Vertical farms are mainly attractive for megacities that historically have been the industrial centers:

1. Megacities depend on external food supplies (since it is economically impractical to grow food in the cities within the framework of the traditional agricultural production model). This provides a negative impact on their food security.

2. In the old industrial centers after deindustrialization there are many abandoned or underused buildings remaining from the former production facilities, as well as adjacent land plots. They are usually used for the construction of residential and commercial real estate, but this leads to a higher occupational density and to deterioration of the urban environment quality.

The construction of the vertical farms allows solving these problems, since they create an opportunity for growing agricultural food products within the city (which favorably affects the supply of food to the cities [5]), and some forms of vertical farms may lead to greening of the cities.

Since vertical farms are based on the active use of digital technologies, they can be easily integrated into a single digital food management system of "smart cities" — a new model of urban management and general governance [87]. Thus, vertical farms correspond to new approaches to urban management based on use of the digital tools [72,88,89]. They can also be easily included into the digital systems of food security that ensure seamless connection between the producers, retail sale chains and the end users.

It means the role of the vertical farms cannot be limited only to direct supplies of fresh food within the cities (without necessity of creation of long supply chains which connect the cities and agricultural areas). Vertical farms also contribute to transformation of urban environment and urban management:

- They help rehabilitate the abandoned industrial buildings by organizing agricultural production there.
- Vertical farms may create green areas within cities. It improves the quality of life of urban population.
- Urban agriculture becomes an integral part of smart cities' management systems. It fosters digital transformation of cities.

It demonstrates the multi-dimensional role of vertical farms in transformation of the cities. It also shows that the owners of former urban industrial sites as well municipal authorities are the active stakeholders of the vertical farm's ecosystems.

3.3. Ecosystem of vertical farms

Vertical farms represent a sub-industry of urban agriculture. It means that the ecosystem of vertical farms is an industrial ecosystem.

According to the classical approach developed by Moore [73] an industrial ecosystem consists of the producers (who make up the core of the industry), the suppliers (both direct and indirect), the competitors and the customers. This approach was developed in further research in order to adapt it to specific industries and to provide more complex view by including the additional groups of the stakeholders [75,76]. Defining the structure of vertical farms ecosystem means adaptation of this general model of industrial ecosystems to the specific features of the vertical farms.

Ecosystem approach to the analysis of industries and analysis of markets has gained its popularity in the scholarly literature and demonstrated its high efficiency for understanding of interactions between the stakeholders in various industries [74,77,90]. Applying this approach towards vertical farms may extend our knowledge of potential conflicts as well as raises the awareness on the models of cooperation between various stakeholders of the vertical farms and contribute to creating a basis for the strategy of development of the vertical farms within the frames of smart cities.

In our opinion this ecosystem can include the following (Table 1):

1. Vertical farm operators are companies that invest in the creation of city farms and then run them. This group of stakeholders constitutes the core of the vertical farms industry. These enterprises generate profit by supplying fresh and higher quality products to the customers. They create value for all other groups of stakeholders of this ecosystem (or, better, they have an impact on the value captured by the other stakeholders). However their development is threatened by the high costs of creating and running the vertical farms (associated with a higher cost of land within the city, as well as boomingly high electricity costs), and, as a result, the possible lower investment attractiveness of such projects.

According to economic calculations provided by iFarm, investments into vertical farms are almost three times higher than investments into the traditional greenhouses of the 4th or 5th generation (https://ifarm-project.ru/technologies#vertical) as their payback period is about 4.3–4.7 years. Vertical farms can be profitable in the big cities only (like Moscow or St. Petersburg).

Operators of the vertical farms have two main groups of the rivals that compete for the investments:

- residential and commercial real estate projects as an alternative option for using urban land. These projects are well known to the investors who are able to evaluate their potential profitability and risks. To the contrary, the vertical farms are a new industry which, despite its high potential, still has unclear prospects. Risk-averse investors may not wish to invest their funds into the vertical farms and would prefer to invest them into the residential and commercial real estate;
- traditional (non-vertical agricultural projects. Traditional agriculture is more transparent for the potential investors in comparison with the vertical farms.

Another problem is that vertical farms are the new companies that still have to create and promote their brands (being surrounded by strong competition with traditional agricultural producers brands). It also decreases the attractiveness of vertical agriculture for investors, which may complicate access to financing. Another factor that hinders the development of vertical farms in Russia is unfavorable legislation. Vertical farms are not considered as the agricultural companies and they have no state support.

Finally, operators of the vertical farms may face a shortage of qualified personnel;

2. Manufacturers of equipment and software for the vertical farms, as well as the developers of projects of such farms and management companies. They are interested in the possibility of making profit from working in a new promising market. These stakeholders face the fact that the growth rates of the vertical farming industry may be lower than they expected.

3. Utilities companies (electric power, water supply etc., as well as those engaged in disposal of agricultural waste). Formally they should be included in the previous group of stakeholders (the suppliers of resources for vertical farms). However, electric power and water are key resources that are necessary for vertical agriculture, and relations between vertical farm operators and utilities companies are often based on non-market basis. Utilities companies are often monopolists and their prices can be established for all groups of the customers. In addition, their supply is stable and inflexible and it may be difficult for these companies to serve the new customers. Actually, the vertical farms may create an additional load for electric power and water supply infrastructure. In the same time the vertical farms may be the good customers for utilities companies as the vertical farms have a stable demand for resources which helps the utilities companies to avoid peaks of consumption.

It is extremely important for vertical farm operators to establish the collaboration with utilities companies and to negotiate good terms.

4. Industrial customers of agricultural products — retail chains and food industry enterprises. The attractiveness of the vertical farming concept for this group of stakeholders is due to the fact that they can simplify their logistics chains, ensure the stability of supplies throughout the year and improve the quality of purchased products (due to the absence of the need for long-term storage and transportation). Negative factors are associated with the possibility of rising prices for the products of vertical farms in comparison with traditional suppliers because of high investments (however, this is offset by the possibility of increasing retail prices for it due to the formation of the image of these products as having better quality).

5. Traditional agricultural producers. On the one hand, vertical farming poses a threat to them, since it is a new model of agricultural organization that competes with traditional models and has important advantages in comparison with them (lower logistics costs and higher product quality) [57]. On the other hand, investing into vertical farms can provide these companies with an opportunity to diversify their business, and due to a stable market position and large financial resources, these enterprises can effectively compete with specialized vertical farm operators. This competition can occur on two levels. First, traditional companies have well-established logistics chains, good connections with retail chains and the ability to supply large volumes of food, and therefore the food products they produce in the traditional way can maintain their competitiveness in comparison with food supplied by vertical farm operators. Second, traditional agricultural companies have the opportunity to invest large resources in vertical farms (including acquisition of their operators) in order to diversify their activities.

6. Land owners who control the access of farms to a key resource. The transition to vertical farms will allow them to diversify models of land management and reduce risks, but, on the other hand, the profitability of vertical farm projects may be lower than alternative projects implemented in cities, which will reduce the income of owners.

7. End consumers (and, more generally, city citizens) interested in having access to quality food (but not willing to pay too high a price for them) [39]. In the same time urban population may not like transformation of areas where they live into large agro-industrial facilities as it may cause harm to the comfort of the city environment;

8. City administration that seeks ways to optimize the usage of urban land, to increase food security and to diversify city economy (all these problems can be solved thanks to introduction of vertical farms). However, city farms may create an additional load on the city infrastructure. It may also hinder transition to post-industrial creative cities. In

Table 1. **Risks and benefits of building vertical farms**
Таблица 1. **Риски и преимущества создания вертикальных ферм**

	Benefits	Risks
For hardware and software manufacturers	— Development of a new technology sales market	— The new market may not be promising enough
For vertical farm operators	— Reduction of wage costs — Water saving up to 90% — Stable harvest — Attracting investments by popularizing the trend of greening — Increase in profits	— Expensive equipment and high operating costs — High electricity costs — Lack of qualified personnel — Possible lower investment attractiveness compared to residential and commercial real estate projects (during the construction of farms within the city)
For utilities companies	— Supply of resource to customers with stable demand: — Cooperation with customers with a high demand (that generates high revenues)	— Additional burden on power and water infrastructure (that may undermine stability of supplies to other customers)
For retail chains and food industry enterprises	— Reduction of transportation costs — Simple logistics chains — Stability of supplies — High-quality locally produced products (which can be used in a marketing strategy)	— The capacity of the farm is insufficient to provide large retail chains — It is advisable to sell products exclusively on the local market
For traditional agricultural companies	— Diversification of production — Well-organized logistics chains — Stable connections with retail chains — Opportunity to invest in vertical farms (absorb competitors)	— Decrease in demand for manufactured products — The threat of displacement from the market
For land owners	— Diversification of the direction of land — Rational use of land resources	— The profitability of vertical farm projects may be lower than alternative projects — Possible decrease of income
For the population (end users)	— Improving the quality of food supply — Transition to organic consumption model — Improving the welfare of citizens by improving the quality of products supplied	— Risks of relatively higher price for the products of vertical farms; — Re-industrialization of cities may harm the urban environment
For city council (municipal authorities)	— Higher food security: — Diversification of urban economy; — Expansion of smart city system	— Load on city infrastructure: — Problem of transition to creative cities; — Low number of jobs created (in comparison to service and creative industries) because of high level of automation of vertical farms
For the state	— Development of the “smart city” concept — Solving the problem of lack of fertile land — Improving the food security situation — Landscaping and land reclamation (on the site of old industrial enterprises) — Improving the efficiency of agriculture	— Depopulation of rural areas — Threat to social stability — High level of consolidated budget expenditures to support the development of vertical farm startups and scientific research in the field of agriculture and technology, as well as to eliminate the negative consequences of depopulation

comparison with creative industries, vertical farms may create less job places (due to a high level of automation) which is a disadvantage from the point of view of local authorities.

9. The state as the main regulator. The state needs to improve the quality of the urban environment and ensure the food security of megacities. At the same time, it seeks to minimize its business support costs (in case of vertical farms development of this new industry may require a substantial support from the state). In addition, the state may fear further depopulation of rural areas and decrease of income (and quality of life in general) of rural inhabitants associated with the transition to vertical farming within the city. This transition may cause destruction of traditional agricultural jobs. This depopulation poses threats to social stability and may require additional resources from the state to overcome its negative consequences.

Stakeholders can combine different roles. For example, Magnit is not only a retail company, but also the independent investor into the vertical farms creation (which corresponds to the policy of this company targeted to minimizing dependence on third-party suppliers). Similarly, iFarm (https://ifarmproject.ru/projects) not only owns farms, but also manages epy vertical farms of third-party owners.

As our analysis shows, the stakeholders not only share their common interests, but also have their contradictions. Therefore, the development of vertical farms will on a large scale depend on the balance of interests of the stakeholders. The state can play an important role in finding this balance by developing a favorable legislative framework and creating incentive measures to encourage investments into the vertical agriculture.

4. Conclusion

Vertical farms as an innovative form of organization agricultural production in the context of the transition to the digital economy have significant and promising potential:

1. First of all, they are a tool for the digital transformation of agriculture [66], which makes it possible to increase the efficiency of food production (by optimizing the usage of land resources, reducing logistics costs and widespread automation of production processes).

2. Due to vertical farms it is possible to improve the food supply of megacities (since food production is organized directly within the cities) and improve the quality of the urban environment.

3. Vertical farms serve as one of the tools for the transition to “smart city”, i. e. the digital transformation of cities [71].

The potential of vertical farms, in accordance with the practice of strategic analysis, can be presented in the form of a strategic matrix below (Table 2). To construct such a matrix, we use the following criteria:

1. Directions of influence of vertical farms — agriculture and cities.

2. The essence of the influence of digital farms — digital and non-digital elements.

Table 2. **Vertical farms potential strategic matrix**
Таблица 2. **Стратегическая матрица потенциала вертикальных ферм**

	Non-digital element	Digital element
Agricultural industry	Improving the efficiency of land use.	Tool for digital transformation of agriculture (based on a new model of organization of food production).
City	— Improving the supply of food to epy cities; — Improving the quality of the urban environment (recultivation of epy old industrial facilities, urban greening and accomplishment).	Transition to the concept of a “smart city” (by building a unified digital management system for the supply of food to cities).

This integrated approach to the very essence of vertical farms and their potential is proposed for the first time. This strategic matrix demonstrates key directions that should be taken into account in state and corporate strategies of development of vertical agriculture.

Important conditions for realizing this potential are:

1. Thorough economic evaluation of vertical farm projects (innovative technologies can be associated with high costs and risks).

2. Coordination of interests of stakeholders in the vertical agriculture industry in order to ensure their cooperation. This coordination is possible both on the basis of a partnership of stakeholders of different groups, and by combining the functions of different stakeholders by one market player (like in the case with Magnit, which simultaneously acts as a retail chain and an operator of vertical farms).

This paper makes an important contribution to the literature on vertical farms by describing the composition of vertical farms' ecosystem and defining the double nature of vertical farms as the tools that can increase efficiency of agricultural production and support transition to smart cities. These results can be used as a theoretical basis for multi-stakeholder approach towards development of strategies of the vertical farms implementation.

The paper also demonstrates the key role of the state in the introduction of vertical farms. The tasks of the state include the following:

1. Finding a balance of interests of different groups of the stakeholders;
2. Creating a favorable environment for development of the vertical farms;
3. Using the vertical farms as one of the tools for the transition to "smart cities" as well as a mechanism to ensure urban food security;
4. Compensation and elimination of negative effects of the vertical farms (prevention of rural areas degradation, etc.).

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Conflict of interest	**Конфликт интересов**
The authors declare no conflict of interest.	Авторы заявляют об отсутствии конфликта интересов.