American Journal of Business and Operations Research

♦ ISSN: 2692-2967 Vol: 12, No. 02, 2025 ♦ PP. 49–54

Article DOI: https://doi.org/10.54216/AJBOR.120206



FULL LENGTH ARTICLE

Development of a Spatial Agent-Based Model for Sustainable Orchard Management: A Study of Environmental and Economic Dynamics

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Received: November 20, 2024 Revised: December 31, 2024 Accepted: January 30, 2025 ⋆ Corresponding author

ABSTRACT

The palm orchards resource is one of the most important economic sources of advantage for the southern and central regions of Iraq. Trees and products obtained from their processing are used in many areas of human life, for example, furniture of various specifications, household and interior items, construction, chemistry, etc. Orchards themselves are also important ecosystems and a necessary element when creating safe living conditions for humans (processing carbon dioxide into oxygen) and plants and animals living in them. Irrational clearing of orchards and trees can not only lead to disruptions in the economic systems of enterprises, but also have a disastrous impact on the health of people living in these territories. In this regard, the purpose of this article is to formalize the system of interaction between objects of the horticultural industry and arable land, which in turn will make it possible to create an effective and rational model of logging at the level of an individual territorial entity. The relationships developed by the authors can be used for a simulation modeling system based on one of the active approaches in development—agent-based modeling. To solve the mentioned problem, general scientific methods such as generalization, systematization, logical-inductive deductions, analysis, scientific synthesis method, etc. were used to determine the specific numerical characteristics of the simulated objects, their parameters and variables. Methods and tools of mathematical statistics were used, tested because of regional statistics of the orchard industry in the Basra region. The results obtained will be useful for forming computer models of orchard management at the regional level, which in turn will allow one to calculate the optimal number of participants in a particular economic direction, and will show the dynamics in which the orchard area will be restored after the removal of orchards. The work carried out by the authors of the study may be of interest to various specialists of the executive authorities involved in the regulation of laws and rights in the forestry sector; commercial enterprises trying to rationalize their activities, while achieving maximum economic returns and efficiency and causing minimal harm to the environment; as well as subject specialists working in the direction of modeling effective simulation systems.

Keywords: Agent-based modeling ▪ Regional orchard complexes ▪ Palm cultivation ▪ Orchard rehabilitation ▪ Agricultural land leasing

1. INTRODUCTION

Effective orchard and palm grove management holds substantial social, economic, and environmental importance on both local and global scales. Poorly planned decisions in orchard

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management, lacking well-founded justifications, may result in adverse environmental impacts, social decline, and the forfeiture of potential economic benefits derived from orchard and palm-based resources.

The state should establish a system for leasing orchards in such a way that tenants can make a significant social and economic impact in the long term without harming the environment. At the same time, the urgent task is to support the decision-making process using simulation models.

From a systems theory perspective, a palm orchard complex can be defined as a dynamic, open, and complex system consisting of several interconnected subsystems. These include the ecological system, social system, production and economic system, public management system, and the external environment. Each subsystem is composed of distinct components, some of which are active agents. These agents interact with each other, leading to changes in system properties and inter-system connections.

In the context of a palm orchard, the ecological system serves as the primary resource base for all other subsystems. It provides essential natural resources such as water, soil, and nutrients, which support palm cultivation and other agricultural activities. The production and economic system, represented by farming companies, utilizes these ecological resources for maximum profit, while simultaneously altering the environment.

The social system involves peasants and workers interacting within the agricultural and economic framework, while the public management system oversees these activities to ensure sustainability. Finally, the external environment, including factors such as market dynamics, climate change, and government policies, influences the complex interactions within the system.

2. PURPOSE OF THE STUDY

The aim of this study is to formalize the interaction system between the entities involved in palm orchards, which will, in turn, enable the development of an effective and rational model for palm cultivation and harvesting at the level of an individual regional entity.

Agent-based modeling techniques are employed as the primary research approach. In this context, we aim to formalize the problem being addressed.

Conceptual Formalization of the Study Area

Consider a specific palm orchard region (T), which is composed of a defined number (N) of orchard zones (LU). Each orchard zone has a designated area size (S), an unspecified biomass volume (without species composition—aggregate index) per hectare (M), and a unique identification code at the regional level (ID). The access coefficient is represented as k^d:

$$LU(ID;S;M,k^d).$$

The total orchard area is:

$$S(T)=\sum_{ID=1}^{N}\mathrm{GET}\big(S;LU(ID)\big). \tag{1}$$

To utilize an orchard of land for orchards and palm cultivation, a lease agreement can be established:

$$DA\big(ID;LU(ID);A(ID);AP;Y_s;Y_f\big). \tag{2}$$

Here, ID is the identifier of the lease agreement; $A(ID)$ is the tenant with the personal identity with whom the agreement is concluded; AP is annual rent; Y_s is the year in which the lease agreement began; and Y_f is the year in which the lease agreement ends.

Each year $(YEAR)$ a certain area $S^-(LU(ID);YEAR)$ is cut down in an orchard area. As a result, the area of possible logging (S^r) decreases. Over a period of K years:

$$S^r(K)=S-\sum_{YEAR=1}^{K}S^-(YEAR). \tag{3}$$

The cultivated area depends on the capabilities of the tenant of the orchard land and the regulations established at the national level for sustainable agricultural practices. The characteristics of sustainability are determined based on the specific features of each orchard, defining the maximum area that can be cultivated within a single year, $S^-_{\max}(LU(ID))$. In cases of exceeding or underutilizing this limit, the tenant may face penalties:

$$PN\big(ID;DA(ID);YEAR;Pn^S\big), \tag{4}$$

where ID represents the fine identifier, $YEAR$ denotes the year the fine was imposed, and Pn^S indicates the fine amount.

The tenant's capabilities can be determined at the level of its size (R) depending on the annual volume of timber harvesting:

$$R=\{sb;b;m;s\}, \tag{5}$$

where sb denotes very large tenants (more than 500 thousand m^3); b denotes large tenants (from 100 to 500 thousand m^3); m denotes medium tenants (from 20 to 100 thousand m^3); and s denotes small tenants (less than 20 thousand m^3).

The tenant's ability to cultivate a specific area of orchard or palm grove land within a year is determined by generating a random variable based on normal distribution functions defined for each type of tenant:

$$S^-_{\max}\big(A(ID)\big)=\mathrm{rand}\Big(\mathrm{GET}\big(R;A(ID)\big);\{p^a_{sb}(s);p^a_b(s);p^a_m(s);p^a_s(s)\}\Big). \tag{6}$$

Here, $p^a_{sb}(s)$ represents the normal distribution function of the maximum possible cultivated area for very large tenants; $p^a_b(s)$ is the normal distribution function for large tenants; $p^a_m(s)$ is the normal distribution function for medium-sized tenants; and $p^a_s(s)$ is the normal distribution function for small tenants. It is important to note that this indicator is calculated based on all orchards managed by each tenant (distributed across them). The total cultivated area attributed to a specific tenant across all leased orchards is determined accordingly.

The methodology for calculating the total area of forest that a renter is permitted to harvest encompasses all rented orchards of land. The total cuttable area for each specific renter is derived from aggregating the available areas across all their leased sites. Furthermore, the permissible harvesting area for

a given orchard in the current year is determined based on specific criteria related to both the limitations imposed on renters and inherent characteristics of the land itself:

$$S^{-}_{LU}\big(A(ID)\big) = \sum S^{-}_{\max}\big(\mathrm{GET}\big(LU(ID); DA(A(ID))\big)\big). \quad (7)$$

The area to be harvested in the current year for a specific orchard of land is determined according to the following criteria and procedures:

$$\begin{aligned} &S^{-}_{LU}\big(A(ID)\big) \le S^{-}_{\max}\big(A(ID)\big): \\ &S^{-}\big(LU(ID); YEAR\big) = S^{-}_{\max}\big(LU(ID)\big), \end{aligned} \quad (8)$$

$$\begin{aligned} &S^{-}_{LU}\big(A(ID)\big) > S^{-}_{\max}\big(A(ID)\big): \\ &S^{-}\big(LU(ID); YEAR\big) = \frac{LU(A(ID))}{S^{-}_{\max}(A(ID))} S^{-}_{\max}\big(LU(ID)\big). \end{aligned} \quad (9)$$

The lessee generates profit from the harvesting of palm trees on a specific orchard of land. This profit depends on the average price per cubic meter of palm tree products (P^t), the harvesting costs (Z^z), the rental fee, and any applicable penalties:

$$\begin{aligned} P\big(DA(ID); YEAR\big) = {} & P^t\,\mathrm{GET}\big(M; \mathrm{GET}(LU(ID)); DA(ID)\big) \\ & \times S^{-}\big(\mathrm{GET}(LU(ID); DA(ID)); YEAR\big) \\ & - Z^z\big(\mathrm{GET}(LU(ID); DA(ID))\big) \\ & \times S^{-}\big(\mathrm{GET}(LU(ID); DA(ID)); YEAR\big) \\ & - \mathrm{GET}\big(AP; DA(ID)\big) \\ & - \mathrm{GET}\big(Pn^S; PN(DA(ID); YEAR)\big). \end{aligned} \quad (10)$$

Harvesting costs are assessed on a per-hectare basis and are influenced by the accessibility of the land orchard. Accessibility is quantified using an accessibility coefficient (K^d), which is uniquely defined for each orchard. The relationship between reduced accessibility and increased harvesting costs is governed by a specific functional dependence f^{zd}. The total costs are expressed as follows:

$$Z^z\big(LU(ID)\big) = f^{zd}\Big(\mathrm{GET}\big(K^d; LU(ID)\big); Z^z\Big). \quad (11)$$

The total profit of the lessee over a period of *YEARS* is determined as follows. In the land orchard, a continuous process of natural change in the volume of palm biomass occurs in the unharvested areas M^+. The predicted value of this change is functionally dependent on the current volume of palm biomass:

$$M^+(YEAR) = f^{pr}_{tm}\big(M(YEAR-1)\big), \quad (12)$$

where f^{pr}_{tm} is the function of the growth in wood biomass.

The volume of wood biomass per hectare of land over a period of K years can be determined as follows:

$$M = M(YEAR-1) + \sum_{YEAR=1}^{K} M^+(YEAR). \quad (13)$$

The lessees are allowed to harvest wood only on those orchards where the established norm of wood biomass per hectare M^N has been exceeded. Otherwise, they face penalty sanctions.

At the conceptual level of the regional agent-oriented model for palm tree harvesting, two agents are defined: the orchard agent and the lessee agent. The orchard agent is responsible for assessing the palm plantation's characteristics, such as growth and biomass, over the modeling period. The lessee agent manages the lease agreement and utilizes the land for cultivation. The agents' behavior models are detailed in the referenced work [1].

3. RESULTS AND DISCUSSION

When developing the model, it is essential to consider the dynamics of the processes involved in shaping the rental environment of agricultural lands in Iraq. The authors conducted an analysis of the dynamics of the agricultural land rental system in Iraq, a country with abundant agricultural resources. Based on available historical data, relationships were established that enable short-term forecasting of changes in the number and area of leased lands, the number of lessees, and the lease duration.

The analysis focused on two key elements of the agricultural land rental system: the agricultural lands leased (lease agreements) and the lessees. The study examined the characteristics of the formation of parameters for these elements and their dynamics over time. The authors relied on publicly available sources of information, primarily data from the Department of Agricultural Resources in Iraq and the Open Data Portal of Iraq. The overall goal of the analysis was to identify trends in the development of the number and area of leased lands [20], as well as the duration of leases. This will facilitate the modeling of changes in their overall structure in the future.

The dynamics of time series illustrating the relationship between the number of orchards leased for palm cultivation are presented in Figure 1. Based on the graphical representation of the dependency, it can be concluded that it exhibits a linear trend. This information can be used for further analysis.

Using the linear approximation tools in Microsoft Excel, the following function for the trend change in the number of lease agreements for palm cultivation was obtained:

$$y = 9.9x - 19455, \quad (14)$$

where the reliability of the approximation is given by $R^2 = 0.6103$.

This function provides a model for forecasting the future number of lease agreements, with the R^2 value indicating a moderate level of fit. Although the approximation shows a reasonable correlation, further refinement and additional data may be necessary for predictions that are more precise.

The equation representing the dependency, obtained through linear approximation, is expressed as:

$$Y = 227537x - 5 \times 10^8, \quad (15)$$

where the reliability of the approximation is given by $R^2 = 0.9048$.

The histogram of the distribution of lease durations is presented in Figure 3.

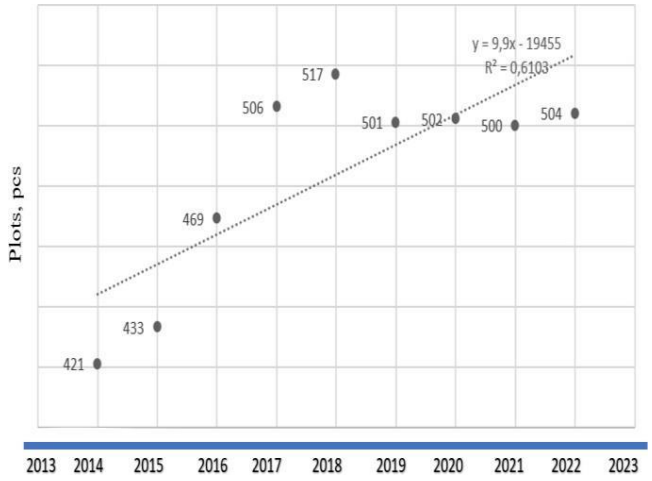


Figure 1. Trends in the number of agricultural land orchards leased for palm cultivation over the years.

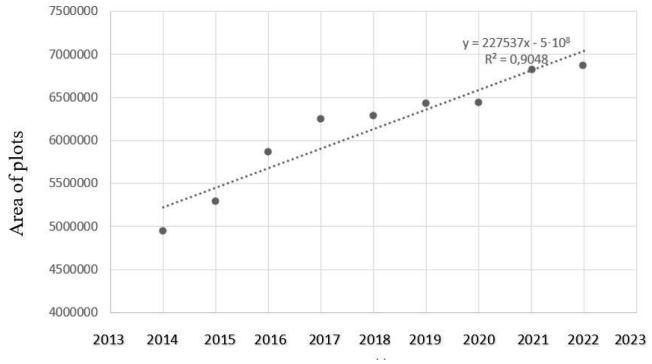


Figure 2. Variation in the area of land parcels under lease agreements for logging purposes.

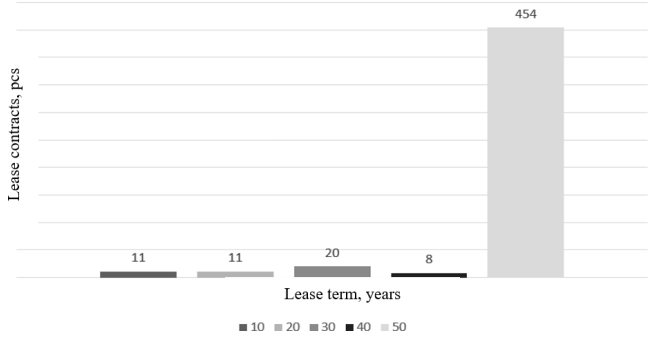


Figure 3. Histogram of the distribution of lease durations for palm-cultivated lands in Iraq.

The coefficient of determination R^2 measures the proportion of the variance in the observed data that is explained by the model. A higher R^2 value indicates a stronger correlation between the model and the data, suggesting a better fit and greater predictive reliability.

The histogram illustrates a marked prevalence of lease agreements with durations exceeding forty years. Given the difficulty in selecting an appropriate distribution model, it is recommended, for the purposes of modeling, to employ a discrete probability distribution to determine the lease duration in the agreements. The intervals and corresponding probability values are derived from the presented histogram, with the understanding that current legislation restricts the permissible lease term for land orchards to a range between 10–49 years.

The primary objective of the analysis of the composition of land leaseholders was to determine the dynamics of changes in their numerical composition, taking into account production capabilities. Leaseholders with different capabilities exhibit distinct behavioral models. Therefore, for the purpose of analysis, leaseholders were categorized into four groups based on their annual timber harvesting volume, in accordance with the formal model presented earlier. It can be assumed that the behavior of each leaseholder in specific situations will resemble the behavior of any other leaseholder within the same group. The relationship between the number of leaseholders and the number of orchards leased by them, categorized by group, over the 2020–2022 period is shown in Figure 4. Notably, while the numerical composition of very large and large leaseholders remains virtually unchanged, the proportion of orchards leased by them increases due to a reduction in the share of orchards leased by smaller leaseholders.

The analysis of time series data concerning the number of palm orchard lessees in Iraq from 2015 to 2022 used linear regression tools available in Microsoft Excel to create trend functions for various categories of lessees, including very large, large, medium, and small groups. Each function delineates how the number of lessees changes over time, with R^2 values indicating the strength of relationships among the studied variables:

$$\text{Very large:} \quad y = 0.3214x + 0.1786, \qquad R^2 = 0.7386, \tag{16}$$

$$\text{Large:} \quad y = 1.4286x + 20.821, \qquad R^2 = 0.6058, \tag{17}$$

$$\text{Medium:} \quad y = 5.369x + 49.714, \qquad R^2 = 0.9043, \tag{18}$$

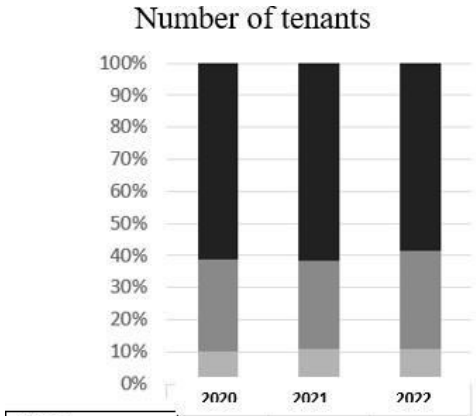
$$\text{Small:} \quad y = -6.4881x + 235.32, \qquad R^2 = 0.7724. \tag{19}$$

These findings reflect the potential utility of statistical models for forecasting future trends in both short- and medium-term contexts, despite temporal limitations that may affect prediction accuracy.

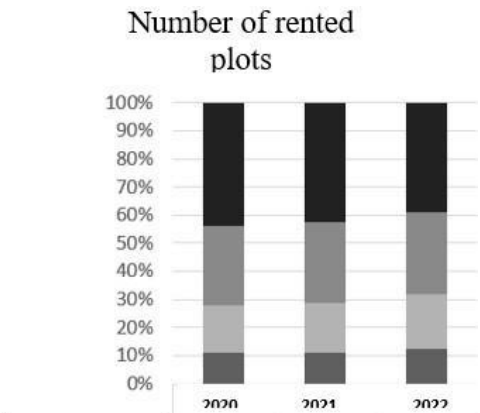
In the development of an intentional model for palm orchards in Iraq, it is possible to adjust its parameters as new data regarding the current state of the modeled system becomes available. This adaptability allows for a more accurate representation and forecasting of trends within agricultural practices related to palm cultivation.

4. CONCLUSION

The dynamics of developing the leasing system for orchards and date palms in Iraq are influenced by various factors, making it challenging to identify their complete list and impact. This article presents methodologies that provide quantitative assessments of trends in this leasing system and forecasts for future parameters. The research contributes to theoretical frameworks for studying the institutional environment surrounding orchard leases in Iraq, highlighting practical significance by enabling stakeholders to identify key trends, construct projections, and apply findings to agricultural models. By utilizing these methodologies, a more accurate descrip-

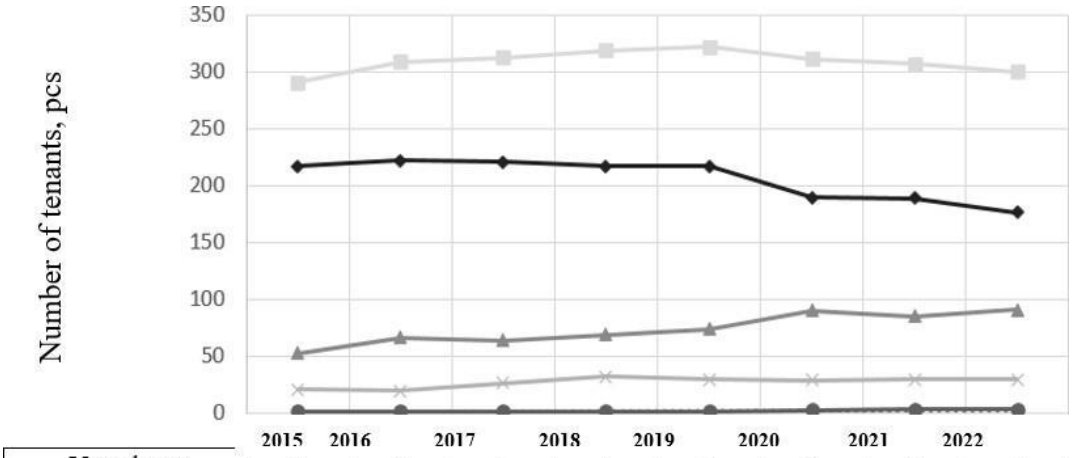


	2020	2021	2022
Small	190	189	176
Average	90	85	91
Large	29	30	30
Very large	2	3	3



	2020	2021	2022
Small	210	205	191
Average	136	138	143
Large	81	83	96
Very large	53	54	61

Figure 4. Ratios of tenants to leased orchards in group.



	2015	2016	2017	2018	2019	2020	2021	2022
Very large	1	1	1	1	1	2	3	3
Large	21	20	26	32	30	29	30	30
Average	52	66	64	69	74	90	85	91
Small	217	222	221	217	217	190	189	176
total	291	309	312	319	322	311	307	300

Figure 5. Time series of palm orchard lessees in agricultural lands in Iraq.

tion of ongoing processes can be achieved through analyzing changes within model elements. This approach is also applicable to other regional agricultural models due to the fundamental nature of the discussed elements.

5. DIRECTIONS FOR FURTHER RESEARCH

This section discusses future research directions in the field of orchards and date palm cultivation in Iraq, utilizing the methods developed by the authors. Their model enhances the understanding of processes related to horticulture and date palm farming by capturing how various elements change over time. This model can also be applied to other regional horticultural structures within Iraq, as the elements it focuses on are fundamental to this field. By employing these advanced methodologies, researchers can investigate the impact of environmental, economic, and social factors on crop production and quality. Furthermore, this approach will aid in developing sustainable strategies for natural resource management while improving agricultural output in line with current climatic changes and economic challenges. Additionally, focusing on orchard cultivation and date palms reflects the significance of these agricultural activities both economically and culturally for Iraq. It provides an opportunity to explore new ways to enhance biodiversity conservation within local and regional contexts.

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