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Statistical yielding models of some irrigated vegetable crops in dependence on water use and heat supply

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Abstract

Statistical analysis is helpful for better understanding of the processes which take place in agricultural ecosystems. Particular attention should be paid to the processes of crops' productivity formation under the influence of natural and anthropogenic factors. The goal of our study was to provide new theoretical knowledge about the dependence of vegetable crops' productivity on water supply and heat income. The study was conducted in the irrigated conditions of the semi-arid cold Steppe zone on the fields of the Institute of Irrigated Agriculture of NAAS, Kherson, Ukraine. We studied the historical data of productivity of three most common in the region vegetable crops: potato, tomato, onion. The crops were cultivated by using the generally accepted in the region agrotechnology. Historical yielding and meteorological data of the period 1990–2016 were used to develop the models of the vegetable crops' productivity. We used two approaches: development of pair linear models in three categories ("yield – water use", "yield – sum of the effective air temperatures above 10°C"); development of complex linear regression models taking into account such factors as total water use, and temperature regime during the crops' vegetation. Pair linear models of the crops' productivity showed that the highest effect on the yields of potato and onion has the water use index (R^2 of 0.9350 and 0.9689, respectively), and on the yield of tomato – temperature regime (R^2 of 0.9573). The results of pair analysis were proved by the multiple regression analysis that revealed the same tendencies in the crop yield formation depending on the studied factors.

Key words: *linear model, multiple linear regression analysis, onion, potato, tomato, yield modelling*

INTRODUCTION

Simulation is an act of imitation directed on artificial and convenient representation of certain real processes by the means of model. Creation and implementation of simulation models for crops' growth, development, productive processes, water and nutrients use, etc., is a new and important branch of modern agricultural science. Since computers had become an irreplaceable part of scientific researches equipment in agricultural studies, a number of attempts to create crop models using different approaches were made. A crop model is a simplified and formalized expression of the real processes, which take place in the natural agricultural system during the crop cultivation period, to make it easier to analyse, generalize, and summarize the real happenings in the system with the purpose of getting the information or prediction related to a number of chosen parameters of the system. Usually, different mathematical or statistical functions are used to describe the above-mentioned natural processes and perform necessary computations in the artificial computer environment [HOOGENBOOM *et al.* 2004]. Currently, modern crop models in agricultural science are divided on two major classes, namely: deterministic and stochastic. The main difference is that deterministic models work with a certain set of organized input data related to crop when stochastic models are more flexible and can effectively handle unorganized and uncertain data sets. Unfortunately, there is no useful and functioning stochastic crop models at the moment.

Deterministic models could also be subdivided into three classes: statistical, mechanistic, and functional models. Statistical models are the oldest among them. First yield simulations were performed using statistical models. For example, corn yields predictions depending on weather were successfully performed by the regression analysis modeling approach using data of a number of years [NELSON, DALE 1978]. Statistical models are especially useful for deep analysis of historical yielding trends.

Mechanistic and functional models use natural and artificial factors of influence on crops (for example, precipitation amounts, nutrients availability, solar radiation income, etc.) to develop simplified mathematical functions for expressing the relationships between the crop productivity, growth and development and the input factors. A well-known example of a functional model is Penman's equation for estimation of crop evapotranspiration [ALLEN *et al*. 1998]. Functional models are also usually used to develop decision support systems, for example, DSSAT [JONES *et al*. 2003].

There is another classification of crop simulation model proposed by PASSIOURA [1996]. It is based on the type of field of model implementation, and it divides crop simulation models on scientific (used for better understanding and investigation of the physiology and environmental interactions of crops) and engineering (used in decision support systems and targeted on providing management advice for farmers). PASSIOURA [1996] also claims that scientific models are mostly mechanistic when engineering models are empirical, need careful calibration and have limitations for usage in different agro-environmental conditions.

Development of modelling approaches in agricultural science and practice is necessary and useful because of opening wide capacities for deep analysis and better understanding of productivity processes in crops, processes, which take place in environment, accurate forecasting, especially, if we are talking about complex models with a hybrid approach to simulation and vast number of the factors related to the crop growth, development and productivity in the concrete agro-environmental system [WHISLER *et al*. 1986]. Besides, even simple crop simulation and predictive models are useful and helps to enlarge our knowledge of plant production. It is believed that reliable crop simulation models lead to considerable improvement of agricultural sector of economy through increased risk management and enhanced crops' cultivation technologies with accordance to the results of simulations.

The main goal of the paper is to present the results of statistical modelling based on the historical data related to vegetable crops productivity (potato, tomato, onion) in dependence on their water use and heat income. The models were targeted on revealing the processes of the crops' productivity and evaluation of the factors input share in their yields in the conditions of the irrigated lands of the Steppe zone.

MATERIAL AND METHODS

Location, climate and soil peculiarities. The vegetable crops (potato, tomato, onion) were cultivated within the period of 1990–2016 at the irrigated lands of the Institute of Irrigated Agriculture of NAAS (Ukr. Instytut Zroshuvanoho Zemlerobstva – NAAN) (latitude 46°44′N and longitude 32°42′E, 43 m above the sea level). The zone of the crops' cultivation belongs to the semi-arid cold steppe zone (BSc) with accordance to the classification provided by Koppen–Geiger climate map [BECK *et al*. 2018]. The climate of the zone is humid continental (Dfa) by Koppen classification. Average annual air temperature is 10.9°C (for the period of 1994–2016) with a tendency to further increase, while annual rainfall averages to 399 mm (by the data of Kherson State Regional Hydrometeorological Center – Ukr. Khersonskyi Derzhavnyi Oblasnyi Hidrometeorologichnyi Tsentr). The vegetable crops were cultivated on dark-chestnut slightly solonets middle-loamy soil, which was developed on loess. The soil is quite typical for the steppe zone of Ukraine. The content of humus in the arable soil layer is 2.15%. The content of nutrients in the soil layer of 0–50 cm was: total nitrogen is 0.17% (determined by the method of calcium chloride extraction in the air-dry soil samples), while the content of mobile phosphorus and potassium were 30–40 and 350–450 mg kg^{-1}, respectively (the nutrients content was determined by the methodology of Chirikov). The power of hydrogen in the arable layer fluctuated between 6.8–7.2 points. Water holding capacity of the soil is 21.5%, total porosity – 45.0%, wilting point – 9.0% (for the 0–100 cm soil layer). Bulk density of the soil in 0–100 cm layer is 1.41 $g \cdot cm^{-3}$. Groundwater is on the depth of 18–20 m, so, it does not affect crops' growth and productivity.

Crops' cultivation technologies and yield evaluation. Vegetable crops were cultivated with accordance to generally accepted technology used in the irrigated conditions of the steppe zone of Ukraine.

The previous crop for potato was winter wheat. In the autumn period, the field was prepared by carrying out harrowing with further plowing on the depth of 28–30 cm. Chisel plowing on the depth of 14–16 cm followed by cresting (the crests of 18–20 cm were formed) was performed after plowing. In the spring the crests were renewed, and soil was loosened by using disk harrow. Fertilization of the crop included application of mineral fertilizers in the dose of $N_{90}P_{90}K_{90}$ placed in the ridges. Planting of potato seed material was conducted when the soil warmed up to 6–8°C on the depth of 10 cm. In the period before sprouting of the crop, we carried out two combined shallow cultivations to keep the crop free of weeds. The irrigation was performed by using the machine DDA-100MA with the working parameters set as "rain intensity" – 0.2–0.3 mm per minute, "diameter of the drip" – 500 μm. To control the quantity of Colorado beetle we used imidacloprid in the dose of 0.2 $kg \cdot ha^{-1}$ at the time of larvae appearance. At the stages of bud emergence and flowering, we applied dimethomorph fungicide in the dose of 2 $kg \cdot ha^{-1}$. Potato tubers were harvested at the stage of biological ripeness after mowing of the vegetative mass by using the motor-scythe Oleo-Mac Sparta 25. Tubers were dug out by the means of motor-block Zubr ZU-15M. Then the tubers were manually collected, sorted and weighed. Only sorted tubers were taken into account in yielding data.

The previous crop for tomato was watermelon. The field was prepared by mouldboard plowing on the depth of 20–22 cm in the autumn period. In the early spring period, several dragging cultivations were performed in the period before pre-sowing cultivation. Tomato seeds were sown by the means of a manual drill SR-1 with the seed rate of 1 kg·ha^{-1}. The total norm of mineral fertilizers applied for the crop fluctuated by the years of the study within the values $N_{297\text{-}373}P_{64\text{-}112}K_{52\text{-}108}$. The insecticide imidacloprid (with the concentration of the active substance of 200 g·dm^{-3}) in the dose of 0.3 dm^3·ha^{-1} was applied to control Colorado beetle. Tomato blight was cured by the fungicide azoxystrobin (with the concentration of the active substance of 250 g·dm^{-3}) in the dose of 0.6 dm^3·ha^{-1}, and complex fungicide folpet (with the concentration of the active substance of 700 g·kg^{-1}) + triadimenol (with the concentration of the active substance of 15 g·kg^{-1}) in the dose of 2.0 kg·ha^{-1}. The crop was also treated with chloranthraniliprole (with the concentration of the active substance of 200 g·dm^{-3}) in the dose of 0.175 dm^3·ha^{-1}. We also performed three shallow inter-row cultivations to control weeds. The irrigation was performed by the means of a drip irrigation system to maintain soil moisture of the active layer at the level of 70–80–70% of the field water holding capacity. Tomato fruit were harvested at once in the 1st decade of September.

The previous crop for onion was winter wheat. After the harvesting of wheat, the field was harrowed and then plowed on the depth of 27–30 cm. Mineral fertilizers in the dose of $N_{120}P_{90}$ were applied in pre-plowing period. In the early spring, two dragging cultivations were performed. The field surface was rolled before sowing of onion. Onion seeds were sown using eight-row ribbon method by the means of a vegetable drill Klen-4.2 with the inter-row spacing of 27 cm. The sowing rate was 5–7 kg·ha^{-1}. Final plant density was formed manually at the stage of 2–3 leaves of the crop. Several inter-row cultivator tillage were performed during the crop vegetation. The irrigation was carried out by using a drip irrigation system. Irrigation pipes were placed between the 2nd–3rd and 6–7th rows. The yield was harvested when 75% of onion leaves wilted. Onion fruit were dug out, placed in rolls and air-dried during 1–2 weeks. Further the fruit were sorted and trimmed, then the yield was evaluated.

Drip tape T-Tape 6 mil with a working pressure of 55 kPa and watering rate of 1.0 dm^3 per hour was used as a basic during the conduction of the trials with drip-irrigated tomato and onion.

Water use and heat income evaluation. Water use (*WU*) of the vegetable crops was calculated by the Equation (1) [GARCIA *et al.* 2009]:

$$WU = ASWU + EPA + IWA \quad (1)$$

Where: *WU* = the water use of the crop, m^3·ha^{-1}; *ASWU* = the amount of soil water used by the crop during the vegetative period, m^3·ha^{-1}; *EPA* = the amount of effective precipitation during the crop vegetation, m^3·ha^{-1}; *IWA* = the amount of irrigation water applied to the field, m^3·ha^{-1}.

The *ASWU* was determined by the Equation (2) as the difference between the soil water content in the 0–100 cm layer at the beginning of crops' vegetation, and in the end of it:

$$ASWU = SWCB - SWCE \quad (2)$$

Where: *ASWU* = the amount of soil water used by the crop during the vegetative period, m^3·ha^{-1}; *SWCB* = the amount of soil water in the 0–100 cm layer at the beginning of the crop vegetation, m^3·ha^{-1}; *SWCE* = the amount of soil water in the 0–100 cm layer in the end of the crop vegetation (before harvesting), m^3·ha^{-1}.

Soil water content was evaluated by the gravimetric method [REYNOLDS 1970].

The effective rainfall was calculated by applying the coefficient 0.6 to the total rainfall during the crop vegetation in the Equation (3). Ineffective rainfall of less than 50 m^3 ·ha^{-1} was not accounted in the calculations:

$$EPA = 0.6\,TPA \quad (3)$$

Where: *EPA* = the amount of effective precipitation during the crop vegetation (m^3·ha^{-1}); *TPA* = the total amount of precipitation during the crop vegetation (m^3·ha^{-1}).

Rainfall was evaluated by using the rain gauge installed nearby the field of the crops' cultivation.

Heat income was assessed by the means of thermometers installed in the vicinity of the field of the crops' cultivation, and it was accounted and expressed as the sum of the air temperatures above 10°C during the crops' vegetative period.

Data analysis. Pair crop models (yield–water use, yield–sum of the air temperatures, etc.) were developed by using linear trend estimation function within Microsoft Excel 2019 software. Complex multiple regression models were developed by using the regression analysis tools of Microsoft Excel 2019 software employing the method of mean squares. All the models were developed at the probability level of 95% ($p < 0.05$) turning on the option "constant – zero".

RESULTS AND DISCUSSION

Historical data sets of the vegetable crops' yields depending on peculiarities of their water use and heat income. We used a historical data containing mean values of the vegetable crops' yields, namely, potato, tomato, onion, which had been obtained during their cultivation within the framework of experimental researches of the Institute of Irrigated Agriculture of NAAS. The yields and the parameters of influence (we mean water supply and air temperatures) were generalized in the Table 1.

The data presented in the Table 1 were used to create pair linear and multiple regression models of the vegetable crops' yields. The columns with the data related to air temperatures and water supply were the inputs, and the yields were the outputs or targets of the models.

Table 1. Yields of potato tubers, tomato fruit and onion bulbs in dependence on the crop water supply and heat income peculiarities within the experimental field researches that were conducted at the irrigated lands of the Institute of Irrigated Agriculture of NAAS, Kherson, Ukraine during 1990–2016

Year	Sum of the effective air temperatures above 10°C	Soil water used	Effective rainfall	Irrigation water applied	Water use	Yield of tubers (t ha^{-1})
		m^3 ha^{-1}				
1	2	3	4	5	6	7
Potato tubers						
1990	1 321.3	995	1 729.1	1 750	4 474.1	24.8
1991	1 428.6	817	1 193.9	2 550	4 560.9	22.4
1992	1 362.5	781	954.5	3 100	4 835.5	26.5
1993	1 359.9	1 432	1 190.2	2 550	5 172.2	23.9
1994	1 608.2	952	1 176.7	2 100	4 228.7	25.8
1995	1 541.4	1 005	2 245.3	1 100	4 350.3	24.7
1996	1 613.7	1 287	1 324.4	1 850	4 461.4	20.2
1997	1 367.8	723	1 931.8	650	3 304.8	39.2
1998	1 574.9	1 153	1 728.0	1 200	4 081.0	25.4
1999	1 595.4	1 060	1 668.2	1 500	4 228.2	23.2
2000	1 506.8	807	1 135.8	1 100	3 042.8	24.9
2001	1 669.0	1 045	1 145.0	1 750	3 940.0	23.5
2002	1 750.8	838	1 007.0	1 800	3 645.0	25.1
2003	1 513.6	550	1 599.0	1 500	3 649.0	22.3
2004	1 344.0	1 107	2 441.0	1 700	5 248.0	30.4
2005	1 697.5	631	1 318.0	1 600	3 549.0	26.1
2006	1 570.3	1 398	1 150.0	2 600	5 148.0	24.6
2007	1 813.5	1 654	470.0	3 000	5 124.0	16.9
2008	1 664.3	2 048	2 048.0	1 600	5 696.0	25.2
2009	993.2	1 088	1 811.0	1 500	4 399.0	21.5
2010	1 822.9	624	1 777.0	1 800	4 201.0	24.4
2011	1 004.7	779	1 239.0	1 400	3 418.0	20.7
2012	1 395.9	692	999.0	2 000	3 691.0	18.3
2013	1 239.1	790	1 235.0	1 800	3 825.0	31.6
2014	1 398.4	882	1 220.0	1 700	3 802.0	30.7
2015	953.9	1 748	2 298.0	1 500	5 546.0	29.1
2016	1 279.1	956	1 363.0	1 800	4 119.0	35.0
Tomato fruit						
1990	1 377.3	1 655	1 842.5	2 400	5 897.5	94.3
1991	1 484.6	849	1 583.1	2 300	4 732.1	75.4
1992	1 418.5	635	1 011.8	2 800	4 446.8	70.1
1993	1 415.9	1 079	1 853.2	2 000	4 932.2	85.1
1994	1 664.2	774	1 468.6	1 500	3 742.6	76.3
1995	1 597.4	810	2 939.4	1 300	5 049.4	97.1
1996	1 669.7	944	1 884.5	1 500	4 328.5	71.6
1997	1 423.8	329	1 388.6	700	2 417.6	83.6
1998	1 630.9	1 060	608.8	2 300	3 968.8	73.2
1999	1 651.4	1 188	1 763.0	1 800	4 751.0	87.0
2000	1 562.8	928	1 536.1	600	3 064.1	88.6
2001	1 725.0	1 207	1 536.1	1 750	4 493.1	88.1
2002	1 806.8	1 025	1 124.2	2 150	4 299.2	75.6
2003	1 569.6	1 287	1 740.5	1 500	4 527.5	84.5
2004	1 400.0	962	2 572.3	400	3 934.3	92.7
2005	1 753.5	149	1 482.6	800	2 431.6	86.4
2006	1 626.3	454	1 232.1	1 300	2 986.1	84.4
2007	1 869.5	694	702.8	1 700	3 096.8	57.9
2008	1 720.3	548	2 671.9	2 400	5 619.9	66.0
2009	1 049.2	169	1 857.0	1 500	3 526.0	65.4
2010	1 878.9	1 702	1 889.5	1 700	5 291.5	71.7
2011	1 060.7	896	1 630.1	900	3 426.1	71.7
2012	1 451.9	682	1 058.8	1 200	2 940.8	63.0
2013	1 295.1	1 126	1 900.2	1 400	4 426.2	69.4

Tab. 1 cont.

1	2	3	4	5	6	7
2014	1 454.4	821	1 515.6	900	3 236.6	73.8
2015	1 009.9	857	2 986.4	1 350	5 193.4	93.3
2016	1 335.1	991	1 931.5	1 450	4 372.5	81.1
Onion bulbs						
1990	1 264.3	734	1 467.7	2 200	4 401.7	78.6
1991	1 371.6	1 104	1 480.5	2 300	4 884.5	83.2
1992	1 305.5	765	608.3	2 500	3 873.3	68.4
1993	1 302.9	544	1 424.3	2 300	4 268.3	82.2
1994	1 551.2	853	1 276.3	1 400	3 529.3	71.4
1995	1 484.4	962	1 902.2	600	3 464.2	66.6
1996	1 556.7	1 435	1 676.0	1 550	4 661.0	94.1
1997	1 310.8	768	1 376.7	750	2 894.7	81.3
1998	1 517.9	658	1 233.4	1 900	3 791.4	104.4
1999	1 538.4	1 262	1 870.1	1 850	4 982.1	84.7
2000	1 449.8	1 301	1 629.7	850	3 780.7	82.4
2001	1 612.0	1 246	1 346.0	1 800	4 392.0	73.1
2002	1 693.8	1 036	809.0	2 000	3 845.0	66.4
2003	1 456.6	547	1 063.0	1 500	3 110.0	81.6
2004	1 287.0	624	1 558.0	1 100	3 282.0	69.6
2005	1 640.5	853	1 133.0	1 200	3 186.0	77.0
2006	1 513.3	775	1 173.0	1 600	3 548.0	64.1
2007	1 756.5	650	574.0	2 000	3 224.0	60.8
2008	1 607.3	801	1 301.0	1 800	3 902.0	92.6
2009	936.2	715	1 634.0	2 000	4 349.0	85.7
2010	1 765.9	765	1 495.0	1 300	3 560.0	67.3
2011	947.7	544	1 520.0	800	2 864.0	77.0
2012	1 338.9	853	656.0	1 500	3 009.0	81.2
2013	1 182.1	467	1 459.0	1 800	3 726.0	81.8
2014	1 341.4	908	1 321.0	1 100	3 329.0	90.8
2015	896.9	665	1 940.0	1 450	4 055.0	101.0
2016	1 222.1	632	1 715.0	1 500	3 847.0	106.6

Source: own study.

Pair models of the crops' productivity in dependence on water use and heat income. The idea of development and introduction in agricultural production of the pair model "crop productivity – water use" is not a new one. For example, LETEY *et al.* [1985] developed a model for the computation of tall fescue (*Festuca arundinacea* Schreb.) productivity in dependence on the crop water supply peculiarities under the conditions of irrigation with saline water. The models related to estimation and analysis of the "crop–water" relationships are believed to be of a great importance and interest for agricultural science and practice, and they are widely developed and implemented in a number of theoretical and practical studies. BAIER [1979] paid a particular attention to the development of theory of "crop–weather" pair models. Our pair models are also strongly connected with weather conditions and their impact on the vegetable crops' productivity in the particular conditions of agricultural production. However, we used different approach to the development of the crops' productivity models. As a result, we obtained a number of pair linear statistical models of the vegetable crops' yields. The models for all the studied vegetable crops are aggregated in the Table 2.

It was established that pair models have high enough level of reliability according to the calculated values of the coefficient of determination R^2 (from 0.9287 to 0.9689).

Table 2. The pair linear models for potato, tomato, and onion productivity depending on the crops' water supply and heat income peculiarities within the experimental field researches that were conducted at the irrigated lands of the Institute of Irrigated Agriculture of NAAS, Kherson, Ukraine during 1990–2016

Crop	Pair linear models of the crops' productivity (t·ha^{-1})	
	yield – water use	yield – sum of the effective air temperatures above 10°C
Potato	$Y = 0.00576X$ ($R^2 = 0.9350$)	$Y = 0.01688X$ ($R^2 = 0.9287$)
Tomato	$Y = 0.01834X$ ($R^2 = 0.9482$)	$Y = 0.05074X$ ($R^2 = 0.9573$)
Onion	$Y = 0.02101X$ ($R^2 = 0.9689$)	$Y = 0.55406X$ ($R^2 = 0.9351$)

Explanations: Y = yield of a particular crop (t·ha^{-1}); X = the independent input variable, expressed in m^3·ha^{-1} for water use (*WU*), and °C for temperature.
Source: own study.

The strongest influence of the temperature regime on the yields was determined for tomato (R^2 of 0.9573), and the yields of onion were mostly affected by the water supply (R^2 of 0.9689), while potato had a moderate response for the studied factors.

The approaches used in the current study for vegetable crops were previously widely and successfully used for cereals. The LINTUL-POTATO model was developed by KOOMAN and HAVERKORT [1995]. The model showed strong dependence of potato tuber yields on the air temperature during the crop growth and development, and, therefore, it is in agreement with the results of our study. Another empirical model developed for determination of water stress affect on potato provided new knowledge on the reaction of potato to water supply [JEFFERIES, HEILBRONN 1991]. Our statistical study provides an additional input to this knowledge providing more food for thought about the peculiarities of potato productivity formation under the different water supply.

CHEN *et al.* [2014] developed and tested several models for tomato "water deficit – yield" relationships assessment. Our linear statistical model for tomato "yield – water use" relations replenishes the current lack of knowledge in this field. The fact that tomato growth, development and productivity are affected by the temperature regime is well-known [CAMEJO *et al.* 2005]. However, there were no many reliable models describing the inter-relation between tomato yields and air temperature. Our statistical model, as the model for greenhouse tomato by JONES *et al.* [1991], is intended to replenish this gap in knowledge. Statistical models together with simulation ones are a valuable tool for better understanding of tomato growth and productivity peculiarities because these models provide more opportunities for deep analysis and investigation of the processes, which take place in the plants during their vegetation under the different agro-environmental conditions.

Onion has got the least number of developed statistical yielding models. SAMMIS *et al.* [2000] created the model of "water – yield" relationship for onion cultivated in New Mexico, USA, mainly focusing on the amounts of water that was artificially applied to the onion field. AL-JAMAL *et al.* [1999] developed the simulation model to fit the irrigation coefficient curve for the best onion yielding response on the basis of the data sets with onion yields and crop coefficients. MISHRA *et al.* [2013] developed the forecasting model of onion cultivation area and productivity by using Autoregressive Integrated Moving Average (ARIMA) approach. The model is based on the historical yielding data of onion cultivated in different areas of India. Most of modern onion models were developed as complex ones, therefore, our study partially replenished current gap in the knowledge related to pair inter-relations between onion bulb yields, water supply level and air temperature.

Complex models of the crops' yield based on the results of multiple regression analysis. Complex statistical models of the vegetable crops' yields of the form $Y = b_1X_1 + b_2X_2$ were created on the basis of the results of multiple linear regression analysis.

The results of regression analysis of potato perennial productivity presented in the Table 3 testify about high reliability of the complex yielding model, which might be developed on the basis of the coefficients presented in the Table 4. The coefficient of determination R^2 is 0.9442 (or 94.42%) that proves strong interconnection between the input factors of the model (which represent water use pattern and heat income) and its output (potato tuber yield).

The model of potato yield in dependence on water use and heat income could be expressed in the form of Equation (4):

$$Y = 0.0033X_1 + 0.0074X_2 \quad (4)$$

Where: Y = the yield of potato tubers (t·ha^{-1}); $X_1...X_2$ = the inputs of the model expressed in °C for the input X_1, and in m^3·ha^{-1} for the input X_2.

As we can see from the model in Equation (4), all the factors had positive effect on potato productivity. The strongest impact is related to the total water use.

The results of the regression analysis of tomato perennial productivity presented in the Table 5 testify about high reliability of the complex yielding model, which might be developed on the basis of the coefficients presented in the Table 6. The coefficient of determination R^2 is 0.9563 (or 95.63%) that proves strong interconnection between the input factors of the model (which represent water use pattern and heat income) and its output (tomato fruit yield).

The model of tomato yield in dependence on water use and heat income could be expressed in the form of the Equation (5):

$$Y = 0.0026X_1 + 0.0103X_2 \quad (5)$$

Where: Y = the yield of tomato fruit (t·ha^{-1}); X_1 = the input of the model expressed in °C for the input X_1, and in m^3·ha^{-1} for the input X_2.

As we can see from the model in the Equation (5), all the factors had positive effect on tomato productivity, but the water use had the strongest effect on the crop productivity.

The results of regression analysis of onion perennial productivity presented in the Table 9 testify about high reliability of the complex yielding model, which might be developed on the basis of the coefficients presented in the Table 10. The coefficient of determination R^2 is 0.9699 (or

Table 3. The results of multiple regression analysis for potato, tomato and onion productivity depending on the crop water supply and heat income peculiarities within the experimental field researches that were conducted at the irrigated lands of the Institute of Irrigated Agriculture of NAAS, Kherson, Ukraine during 1990–2016

Regression statistics		Analysis of variance (ANOVA)			
		statistical criteria	regression	residue	total
Potato					
Multiple coefficient of correlation (R)	0.9717	degrees of freedom (DF)	2	25	27
Coefficient of determination (R^2)	0.9442	sum of squares (SS)	17050.9492	1007.7108	18058.6600
Normalized R^2	0.9020	mean square (MS)	8525.475	40.3084	
Standard deviation (SD)	6.3489	F-statistics	211.5060		
Observations (N)	27	F-significance	$5.74 \cdot 10^{-16}$		
Tomato					
Multiple coefficient of correlation (R)	0.9779	degrees of freedom (DF)	2	25	27
Coefficient of determination (R^2)	0.9563	sum of squares (SS)	171038.4499	7819.5401	178857.9900
Normalized R^2	0.9145	mean square (MS)	85519.2250	312.7816	
Standard deviation (SD)	17.6856	F-statistics	273.4151		
Observations (N)	27	F-significance	$3.05 \cdot 10^{-17}$		
Onion					
Multiple coefficient of correlation (R)	0.9848	degrees of freedom (DF)	2	25	27
Coefficient of determination (R^2)	0.9699	sum of squares (SS)	173467.5325	5390.4575	178857.9900
Normalized R^2	0.9287	mean square (MS)	86733.7663	215.6183	
Standard deviation (SD)	14.6840	F-statistics	402.2561		
Observations (N)	27	F-significance	$3.49 \cdot 10^{-19}$		

Source: own study.

Table 4. The coefficients (with related statistics) used in the model of potato, tomato and onion productivity depending on the crop water supply and heat income peculiarities within the experimental field researches that were conducted at the irrigated lands of the Institute of Irrigated Agriculture of NAAS, Kherson, Ukraine during 1990–2016

Model inputs	Coefficient (b)	Standard deviation (SD)	t-statistics	P-value
Potato				
Input X_1	0.0033	0.0017	2.6313	0.0014
Input X_2	0.0074	0.0029	2.0267	0.0535
Tomato				
Input X_1	0.0026	0.0088	2.9400	0.0070
Input X_2	0.0103	0.0030	3.4803	0.0019
Onion				
Input X_1	0.0080	0.0090	0.8896	0.3822
Input X_2	0.0181	0.0034	5.3700	$1.44 \cdot 10^{-5}$

Explanations: input X_1 = sum of the effective air temperatures above 10°C; input X_2 = total water use ($m^3 \cdot ha^{-1}$).
Source: own study.

96.99%) that proves strong interconnection between the input factors of the model (which represent water use pattern and heat income) and its output (onion bulbs yield).

The model of onion yield in dependence on water use and heat income could be expressed in the form of Equation (6):

$$Y = 0.0080X_1 + 0.0181X_2 \quad (6)$$

Where: Y = the yield of onion bulbs ($t \cdot ha^{-1}$); X_1 = the input of the model expressed in °C for the inputs X_1, and in $m^3 \cdot ha^{-1}$ for the input X_2.

As we can see from the model in the Equation (6), all the factors had positive effect on onion productivity. The strongest impact on the yields of onion caused the water supply.

The complex models revealed that the most susceptible to the temperature regime and water supply crop among the studied ones is onion, and the least susceptible crop to water stress is potato, while tomato is moderately susceptible to both water and heat supply during the vegetation period.

We are not the first to implement mathematical statistics to the analysis and modelling of vegetable crops' productivity in dependence on the agro-environmental conditions of their cultivation. YARTZ and MOORE [1978] provided a model of potato tubers yield in dependence on the temperature and insolation data. They used mean daily temperatures of the air and insolation income as the inputs for the evaluation and prediction of potato productivity. The model's reliability was proved by comparatively high coefficient of determination R^2 of 0.93. A similar approach to those we have used in our study was implemented by HAVERKORT and HARRIS [1987] for modelling potato growth and productivity under tropical highland conditions. Their model was based on the climatic data and yields of the crop during the period of 1984–1985. The results obtained in the study testify that the best modelling results were provided by the quadratic model of potato yield.

A similar analysis of historical yielding data of 12 common for California crops was performed by LOBELL *et al.* [2007]. The scientists have analysed perennial data set of the crops yields (including various vegetables, fruits and buts) and linked them to the weather conditions of the period, namely: minimum temperature, maximum temperature and precipitation. As a result, LOBELL *et al.* [2007] stated that such models are very prospective for forecasting the yields of crops by using the "yield – climate" relationships.

Complex simulation model of onion productivity named ALCEPAS, which is based on the Simple and Universal Crop Growth Simulator (SUCROS87), was developed and validated by DE VISSER [1994a; 1994b]. Onion crop behaviour in dependence on water supply conditions was also modelled using the MOPECO model by DOMINGUEZ *et al.* [2011]. However, it seems to us that we were the first to develop the complex yielding model of onion bulbs by using the multiple regression analysis in dependence on a number of environmental factors.

Regression-based models are widely used for yielding modelling of different crops depending on various agro-environmental and technological factors, primarily; they are used for grain crops [GORNOTT, WECHSUNG 2016]. For example, ENGELSTAD [1968] implemented multiple regression analysis to the assessment of different fertilizers. BUTT and ROYLE [1974] used multiple regression analysis for better understanding of plants' diseases occurrence, distribution, and management. We proposed the models based on the multiple linear regression analysis to predict the vegetable crops' yields in dependence on the water supply and heat income. However, it is still a debatable question whether such models are better or worse than simulation and empirical models of crop growth, development and productivity. We also believe that implementation of modern remote sensing methods and satellite observations and measurements might drastically improve the accuracy of crop models and improve the approaches used for the development of crop models. For example, MUKHERJEE and SASTRI [2004] developed the model for prediction of tomato fruit yield based on the remote sensing analysis. Besides, non-linear regression models should be better for agricultural purposes than linear ones. TEI *et al.* [1996] reported that the best reliability was obtained by modelling onion growth through the expolinear function. However, their better performance is connected with their higher complexity and difficulties regarding their development. The study conducted by ZOBEL *et al.* [1988], which was devoted to the comparison of four approaches to statistical analysis of soybean yield trials, showed that the best results were obtained through the implementation of complex additive main effects and multiplicative interaction model (AMMI) while the performance of linear regression model was limited due to the small range of the interactions accounted by the model. Another prospective technique to improve the predictive crop modelling is artificial neural network modelling. Therefore, further studies and researches in the field of crops' productivity modelling should be conducted because we finally have to come with a conclusion what type of models (statistical, empirical, simulation or combined) fits best for practical and scientific needs. Nowadays, we have a few functioning combined models of vegetable crops. The good example is the model developed by FAN *et al.* [2015] for evaluation of tomato growth. The model is a knowledge-and-data-driven one, and consists of two inter-connected submodels: GreenLab knowledge-driven model, and the radial basis function network model, which are efficiently linked.

CONCLUSIONS

The results of the modelling revealed some peculiarities of the vegetable crops' productivity in dependence on their water use and heat supply. It was determined that the strongest correlation between the crop productivity and air temperatures was in tomato, where R^2 value of the pair model was 0.9573. The most susceptible to water stress crop was onion (R^2 value of the pair model was 0.9689). Potato is considered to be moderately susceptible to both water and heat stress. The complex models just proved the tendencies discovered through the pair modelling approach, and provided more insights into the yield formation peculiarities for the studied crops in dependence on the factors engaged in the research.

Further investigations in the field of crops' growth and productivity modelling should be carried out to provide more reliable and precise mathematical computations and simulations of crops' development patterns in dependence on different agrotechnological and natural factors. We believe that the future is for the complex agricultural modelling approaches that should provide the tool for comprehensive and reliable simulation of the whole variety of biological processes, which take place during crops' production.

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