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Water-Food-Energy: Nexus and Non-Nexus Approaches for Optimal Cropping Pattern

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Abstract Given the water-food-energy interconnections, integrated planning, policy and management using the nexus approach are required for the food production system. In this study the nexus and non-nexus approaches are compared to propose an optimal cropping patternthat considers water, energy and economic parameters. Linear optimization was applied to compare i) the nexus approach utilizing an objective function to maximize a water-food-energy nexus index and 2) the non-nexus approach utilizing three objective functions for water use, energy use, and agricultural net return. The study showed that the nexus approach is the best. Applying it through a water-food-energy nexus index provides a holistic method for identifying an optimal cropping pattern that reduces water and energy consumption and increases the agricultural net return.

Keywords Nexus index · Multi-objective optimization · Minimizes water use · Minimize energy use · Cropping pattern

1 Introduction

The interactions among water, energy, and food are numerous and decisions about any of the sectors without considering their interconnections may lead to acute negative consequences

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(Bizikova et al. 2013; Hoff 2011; Bonn 2011; FAO 2014a). Recognizing their interdependence is critical because global agricultural projections indicate that the need for water, energy, and food will increase significantly over the next decades due to the pressure of drivers such as population growth, economic development, cultural and technological changes, and climate change. Irrigated agriculture accounts for 70% of total global freshwater withdrawals, and the food production and supply sequence uses about 30% of total energy consumed globally (FAO 2012, 2014b). With water and energy scarcity, one of the principal concerns is the optimum usage of available resources to provide food security and progress toward Sustainable Development Goals (SDGSs).

Responsibility to attain optimal use of available resources falls mainly into national water resources and agricultural policy arenas. The present water policy in many countries aims at increasing available water resources through irrigation improvement and changing cropping patterns. This leads to enhancement of water supply management while maximizing economic, social, and environmental returns.

The research reported here focuses on comparisons between nexus and non-nexus approaches for cropping pattern adjustments to support the optimal use of water and energy. The study shows how the nexus approach can be used effectively to consider economics and environmental issues along with food and energy. Data from cropping patterns in Egypt are used to assess and validate the proposed method.

The background of the research indicates that adjustments of cropping patterns for optimal use of water resources show high levels of global research interest. Most studies focus on optimal use issues taking into account the economic return of the cropping pattern (Kaushal et al. 1985, Mayya and Prasad 1989, Paudyal and Gupta 1990, Shahata 1993, Abu-Zeid 1998, Keith et al. 1998, Sethi et al. 2002, Salah 2002, Nimah 2004, Negm et al. 2006, Shahata and Raghab 2008, Fawzy 2009, Kaur et al. 2010, PS 2012, MWRI 2012**,** El-Gafy et al. 2013, El-Gafy 2013). A number of other studies consider a multi-objective optimization approach with optimal use of water while considering the environment and land use as well (Xevi and Khan 2012, El-Gafy 2013). The objective function applied in the previous studies focus only on minimizing water use and maximizing net return and the studies address the optimal cropping pattern issue without considering the water-energy–food nexus.

Results of this study can be applied in countries with different approaches to farm policy. The study region of Egypt uses a national planning approach, which can use the methodology directly. A large country such as the United States can use the methodology to evaluate national cropping patterns in diverse regions, leading to reforms in farm policies.

2 Methodology

2.1 Non-Nexus and Nexus Approaches

To compare non-nexus and nexus approaches, summer optimal cropping patterns for Egypt are proposed under five scenarios, as illustrated in Fig. 1. Four of the scenarios represent the non-nexus approach. Under Scenario 1 (Sc_1), the cropping pattern is the same as it is currently. Under Scenario 2 (Sc_2), Scenario 3 (Sc_3), and Scenario 4 (Sc_4)the proposed cropping patterns are to minimize water use, minimize energy use, and maximize agricultural net return respectively.

The fifth scenario, Scenario 5 (Sc_5), represents the nexus approach through maximizing the Water-Food-Energy Nexus Index (WFENI). WFENI is an index that illustrates the performance of water-food-energy management by integrating major variables of the nexus. Its significance is integrating a number of aspects that reflect major concerns in the water-food-energy nexus into a single number to assess and compare strategies (El-Gafy et al. 2017, El-Gafy 2017).

2.2 Optimization Models

Comparison of the scenarios is achieved by applying four linear optimization models to simulate the non-nexus and nexus approaches. The non-nexus approach is assessed by utilizing the objective functions within linear programmingoptimization models to minimize water use (Sc_2), minimize energy use (Sc_3), and maximize agricultural net return (Sc_4), as shown in Eqs. 1 to 3:

$$Min.W = \sum_{i=1}^{r} w_i \times A_i \tag{1}$$

$$Min.E = \sum_{i=1}^{r} e_i \times A_i \tag{2}$$

$$Max.N = \sum_{i=1}^{r} N_i \times A_i \tag{3}$$

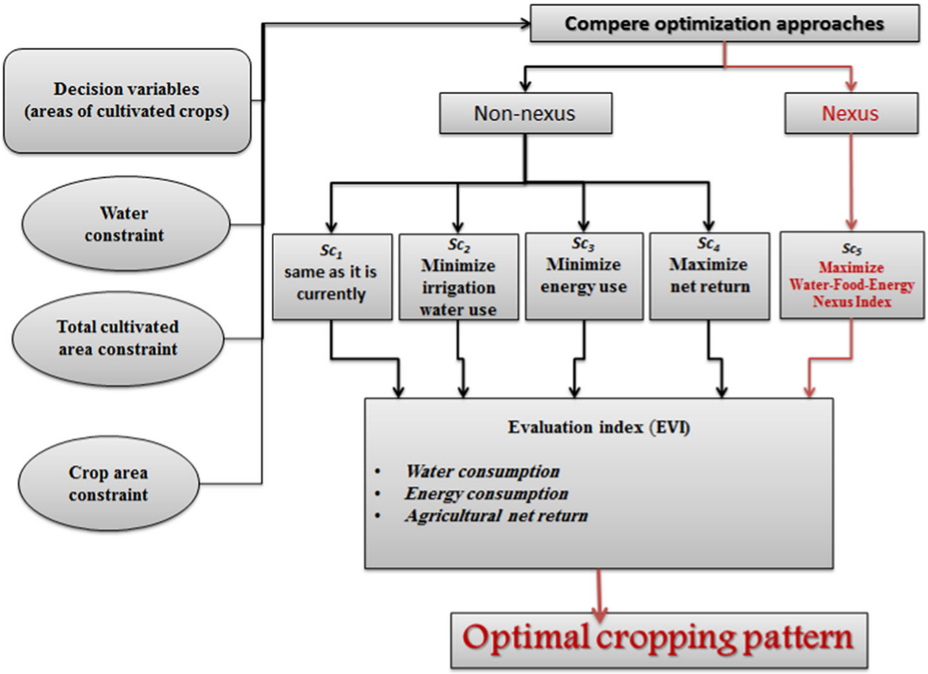

Fig. 1 Methodology frame work

Where: w_i (m^3/ha) is the water required per ha for crop *(i)*, e_i (J/ha) is the energy input per ha from crop *(i)*, N_i ($/ha) is the net return per ha from crop *(i)*, A_i (ha) (decision variable) is the cultivated area of crop *(i), r* is the number of crops of the study.

The fourth model was developed to demonstrate the nexus approach. Its objective function is to maximize WFENI, as shown in Eq. 4.

$$Max.z = \sum_{i=1}^{r} WFENI_i \times A_i \tag{4}$$

Where: $\boldsymbol{WFENI_i}$ is the water-food-energy nexus index of crop *(i)*, $\boldsymbol{A_i}$ is the cultivated area of crop *(i)*, and *r* is the number of crops of the study. WFENI is a composite of indicators that represents the interrelation between water-food-energy, as shown in Fig. 2, which also indicates where interventions would take place to improve the nexus. The interrelation between water and food is addressed through water consumption, water mass productivity, and water economic productivity indicators. The interrelation between energy and food is measured by energy consumption, energy mass productivity and energy economic productivity indicators. Finally, the interrelation between energy and water is represented through energy consumption for irrigation. The components of WFENI (j) are combined utilizing Eq. 5 (EL-Gafy et al. 2017, EL-Gafy 2017):

$$\boldsymbol{WEFNI} {=} \textstyle\sum_{i=1}^{j} w_i X_i \Big/_{\sum} \boldsymbol{i} = 1^{j} \boldsymbol{w_i} \tag{5}$$

Where: X_i refers to WFENI's normalized indicator *i*, w_i is the weight applied to each component and *(j)* is the number of WFENI variables. The highest value 1 is taken to be the best situation while 0 is the worst. According to the weights, equal values are given in this study for the different crops.

The indicators of WFENI are normalized in order to exclude the influence of different dimensions by applying the Min-Max normalization technique as in Eqs. 6 and 7. Equation 6

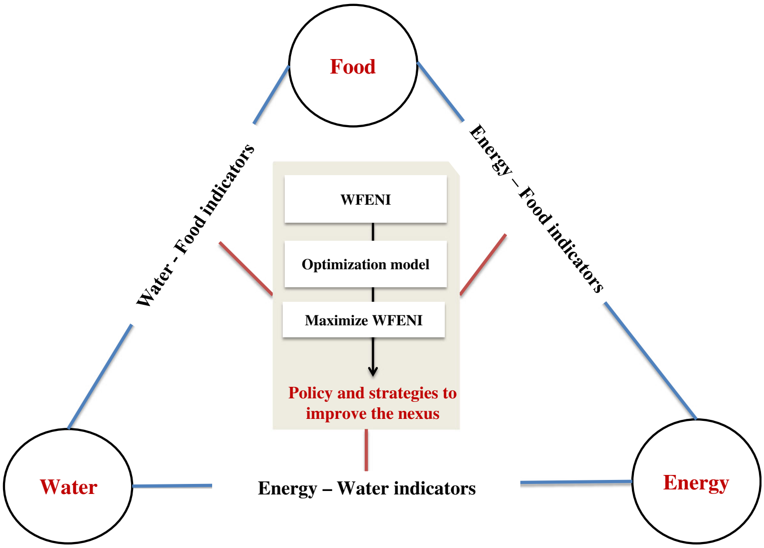

Fig. 2 Interrelation between water-food-energy within WFENI

Table 1 Food-Water-Energy nexus index indicators

Crop	Consumption[a]		Mass productivity[a]		Economic[b] productivity	
	Energy[c] MJ/ha	Water m^3/ha	Energy Kg/MJ	Water Kg/m^3	Energy \$/MJ	Water \$/m^3
Onion	42,342	6044	0.68	4.77	0.09	0.63
Tomato	44,971	6621	0.87	5.93	0.05	0.35
Pepper	28,106	6599	0.60	2.55	0.03	0.14
Potato	53,621	6404	0.51	4.26	0.04	0.33
Quintalob	52,633	7490	0.65	4.59	0.02	0.15
Pea	36,220	5248	0.30	2.04	0.02	0.16
Okra	47,148	7982	0.26	1.55	0.05	0.30
Watermelon	52,705	7679	0.59	4.02	0.03	0.18
Zucchini	31,339	5446	0.21	1.21	0.02	0.14
Peanut	33,515	10,606	0.09	0.29	0.04	0.14
Sugarcane	63,507	21,429	1.69	5.00	0.03	0.08
Soybean	29,679	7660	0.13	0.49	0.01	0.06
Sunflower	31,640	6040	0.09	0.46	0.01	0.04
Eggplant	49,510	6425	0.20	1.53	0.02	0.13
Maize	42,366	7143	0.17	1.00	0.01	0.07
Sesame	36,697	6660	0.03	0.19	0.01	0.07
Sorghum	42,293	7619	0.13	0.74	0.01	0.05
Cucumber	47,311	7921	0.03	0.19	0.01	0.09
Rice	44,143	15,117	0.19	0.57	0.02	0.05

The table is sorted according to the value of the WFENI that is illustrated in Table 2

[a] Sources: El-Gafy et al. 2017, El-Gafy 2017

[b] Source: EAS, 2014

[c] The energy consumption including the energy consumed through human labor, machinery, diesel oil, electricity, fertilizer, pesticides, seeds, and irrigated water inputs in the crop production

is used when the Min(x_i) of the indicator is the least preferred value and Max (x_i) is the most preferred value, where Eq. 7 is used for the opposite situation.

$$X_i = \frac{x_{ia} - Min(x_i)}{Max\ (x_i) - Min(x_i)} \tag{6}$$

$$X_i == 1 - \frac{x_{ia} - Min(x_i)}{Max\ (x_i) - Min(x_i)} \tag{7}$$

Where: x_{ia} is the actual value of WFENI's indicator i.

2.3 Constraints

The objective functions in the four models are subjected to constraints for area, water, and energy as presented by Eqs. 8, 9, and 10 respectively.

Area constraint:

$$\sum_{i=1}^{r} A_i \le A_a \tag{8}$$

Where: A_{is} the cultivated area by crop (i) at season s, A is the total area cultivated at in season *(s)*, r is the number of cultivated crops and s is the season.

Water constraint:

$$\sum_{i=1}^{r} w_i \times A_i \leq W_a \tag{9}$$

Where: $\boldsymbol{W_a}$ is the available water for irrigation.

Energy constraint:

$$\sum_{i=1}^{r} e_i \times A_i \leq E_a \tag{10}$$

Where: $\boldsymbol{E_a}$ is the available energy for agricultural. Energy requirements includes energy of human labor, machinery, diesel oil, electricity, fertilizer, pesticides, seeds, and irrigated water inputs for crop *(i)* production.

2.4 Evaluation Index

The Evaluation index (**EVI)** is applied to determine the best scenario. This index is the average summation of three evaluating indicators for water consumption (W), energy consumption (E), and agricultural net return (N). The four indicators are combined utilizing Eq. 11. The indicators of **EVI** are normalized in order to exclude the influence of different dimensions applying the Min-Max normalization technique. The highest value of **EVI** is taken to the best scenario.

$$\boldsymbol{EVI}=(\mathbf{W}+\mathbf{E}+\mathbf{N})/3 \tag{11}$$

Table 2 Food-Water-Energy nexus index and its normalized indicators

Crop	Consumption		Mass productivity		Economic productivity		WFENI
	Energy	Water	Energy	Water	Energy	Water	
Onion	0.60	0.95	0.39	0.80	1.00	1.00	0.79
Tomato	0.52	0.92	0.51	1.00	0.54	0.53	0.67
Pepper	1.00	0.92	0.34	0.41	0.32	0.18	0.53
Potato	0.28	0.93	0.29	0.71	0.38	0.48	0.51
Quintalob	0.31	0.86	0.37	0.77	0.17	0.19	0.45
Pea	0.77	1.00	0.16	0.32	0.20	0.21	0.44
Okra	0.46	0.83	0.14	0.24	0.53	0.45	0.44
Watermelon	0.31	0.85	0.33	0.67	0.22	0.23	0.44
Zucchini	0.91	0.99	0.11	0.18	0.20	0.16	0.42
Peanut	0.85	0.67	0.04	0.02	0.44	0.17	0.36
Sugarcane	0.00	0.00	1.00	0.84	0.23	0.07	0.36
Soybean	0.96	0.85	0.06	0.05	0.08	0.03	0.34
Sunflower	0.90	0.95	0.03	0.05	0.00	0.00	0.32
Eggplant	0.40	0.93	0.10	0.23	0.12	0.16	0.32
Maize	0.60	0.88	0.08	0.14	0.05	0.05	0.30
Sesame	0.76	0.91	0.00	0.00	0.07	0.05	0.30
Sorghum	0.60	0.85	0.06	0.10	0.02	0.02	0.27
Cucumber	0.46	0.83	0.00	0.00	0.08	0.08	0.24
Rice	0.55	0.39	0.10	0.07	0.12	0.02	0.21

Table 3 Water-food-energy nexus change due to the proposed cropping pattern under different scenarios

CROP	Cropping pattern (ha)					Water (MCM)					Energy (TJ)					Net return (Million $)				
	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
Maize	799	1013	989	990	983	5705	7233	7061	7070	7022	33,836	42,901	41,881	41,936	41,650	3116	3951	3857	3862	3835
Rice	575	403	403	403	403	8692	6085	6085	6085	6085	25,383	17,768	17,768	17,768	17,768	3383	2368	2368	2368	2368
Sorghum	140	98	181	98	98	1063	744	1382	744	744	5901	4131	7672	4131	4131	410	287	534	287	287
Sesame	32	41	41	22	22	211	274	274	148	148	1161	1510	1510	813	813	117	152	152	82	82
Sunflower	15	19	19	10	19	89	115	115	62	115	464	604	604	325	604	27	35	35	19	35
Peanut	33	23	43	43	43	353	247	459	459	459	1116	781	1451	1451	1451	384	269	500	500	500
Soybean	7	5	9	5	9	53	37	69	37	69	206	144	268	144	268	23	16	30	16	30
Sugarcane	132	92	92	92	92	2829	1980	1980	1980	1980	8384	5869	5869	5869	5869	1731	1212	1212	1212	1212
Tomato	79	103	55	103	103	523	680	366	680	680	3551	4616	2486	4616	4616	1448	1882	1013	1882	1882
Watermelon	28	19	19	36	36	213	149	149	277	277	1464	1025	1025	1903	1903	295	207	207	384	384
Eggplant	14	18	10	18	18	91	118	63	118	118	698	907	488	907	907	93	121	65	121	121
Zucchini	12	16	16	16	16	67	87	87	87	87	386	502	502	502	502	71	93	93	93	93
Cucumber	10	7	7	14	7	82	58	58	107	58	492	344	344	639	344	55	39	39	72	39
Quintalob	9	6	6	12	12	68	48	48	89	89	480	336	336	624	624	82	57	57	106	106
Potato	47	61	33	61	61	299	388	209	388	388	2500	3251	1750	3251	3251	757	985	530	985	985
Pepper	13	17	17	17	17	88	115	115	115	115	377	490	490	490	490	99	129	129	129	129
Okra	4	3	3	5	5	29	21	21	38	38	173	121	121	225	225	69	48	48	90	90
pea	6	8	8	8	8	34	44	44	44	44	233	303	303	303	303	43	56	56	56	56
Onion	6	8	8	8	8	39	51	51	51	51	273	355	355	355	355	192	249	249	249	249
Total	1961	1961	1961	1961	1961	20,528	18,473	18,636	18,579	18,566	87,079	85,957	85,222	86,252	86,074	12,396	12,156	11,174	12,512	12,482

Table 4 Evaluation index (**EVI**) of Water-food-energy nexus under different scenarios

	Scenarios				
	Non-nexus				Nexus
	C1	C2	C3	C4	C5
Evaluation indicators					
Water	20,528	18,473	18,636	18,579	18,566
Energy	87,079	85,957	85,222	86,252	86,074
Net Return	12,396	12,156	11,174	12,512	12,482
Normalized indicators					
Water	0.00	1.00	0.92	0.95	0.95
Energy	0.00	0.60	1.00	0.45	0.54
Net Return	0.91	0.73	0.00	1.00	0.98
Evaluation Index (**EVI**)	0.30	0.78	0.64	0.80	0.82

3 Results and Discussion of Egyptian Data

3.1 Determination of WFENI

The indicators of WFENI were determined for 19 summer Egyptian crops, Table 1. These indicators were normalized using Eqs. 6 and 7 and the final WFENI was determined applying Eq. 5. The normalized indicators and the final WFENI are shown in Table 2. Onion had the highest WFENI with value 0.79 and rice the lowest value among the 19 crops with value 0.21. Onion has four indicators (water and energy economic productivity, water and energy consumption, and water mass productivity) with high scores that lie between 1.0 and 0.6, Table 2. Rice has comparative lower indices between 0.02 and 0.55, Table 2.

3.2 Evaluating Non-Nexus and Nexus Approaches

The change in water-food-energy nexus due to the proposed cropping pattern under different scenarios is illustrated in Table 3. The total cultivated area under the different scenarios will be same as it is currently. The water, energy, and net return will be different according to the objective of each scenario. Sc_1 has **EVI** with scores 0 for water and energy use. Sc_1 is the worst scenario for reducing the water and energy use. Sc_5 (the nexus approach) is the best scenario as it has the highest EVI with value 0.82. Sc_5 is followed by Sc_4, Sc_2, Sc_3, and Sc_1 respectively, as shown in Table 4.

4 Conclusion

The research reported here focuses on comparing nexus and non-nexus approaches to develop strategies for cropping patterns adjustments to lead to optimal use of water and energy. The results illustrate that the proposed cropping pattern applying the nexus concept is the best approach. This result is achieved by utilizing the objective function in an optimization model to maximizethe water-food-energy nexus index.

Compared to the current cropping pattern, the nexus approach saves water andenergy and increases agricultural net return more than the non-nexus approch. The annual water and energy saving might approach 1.9 BCM and 1006 TJ respectively. About $86 million per year in economic return could be gained if the nexus approach is applied to propose optimal cropping pattern.

The result of the study shows that attention to inter-linkages of the water, energy, and food nexus, along with implications for sustainable development and adaptation, must be considered when developing national polices and strategies.

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