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Modelling the Water-Energy-Food-Land Use-Climate Nexus: The Nexus Tree Approach †

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Abstract: The United Nations Food and Agriculture Organization (FAO) has established the Water-Energy-Food Nexus, implying that the three commodities are inextricably linked forming a complex system of interrelations. Perceiving water, energy and food as a system variable with dependencies rather than a singularity suggests an approach of a more holistic view that can offer a sustainable plan for managing resources. In this article, the already established three-way Nexus is expanded to include two more dimensions, namely land use and climate and a framework for modelling the interlinkages among these dimensions is presented.

Keywords: nexus; sustainability; resource efficiency; complex systems

1. Introduction

The concept of integrated management of natural resources has been in use for years; however, the complex interlinkages and interdependencies amongst individual resources are still not clearly defined, creating difficulties in the development and implementation of this concept [1]. As a result, responding to a challenge in the management of one resource, such as water, often creates challenges for the management of others, such as energy, or food. The collective and integrated management of these resources using a Nexus approach should be used to increase resource-use efficiency and minimize environmental risks and ecological degradation [2]. Even though the Nexus concept has been present in the sustainable development rhetoric for a few decades, it has only gathered a lot of attention within scientific and policy disciplines over the last ten years [3], especially including the interactions across the Water-Energy and Water-Energy-Food domains [4], which become critical as the pressures of population growth and climate change increase. Lately, the Nexus concept has been expanding to also include other resources [5], commodities and/or disciplines, such as land use, soil, waste, climate, economy, ecosystems, health and others, making the Nexus even more multi-dimensional and interdisciplinary. New innovative tools, such as a serious game, are being developed to make the Nexus concept more accessible and comprehensible by policy-makers and citizens alike, through innovative participatory processes and following a bottom-up approach [6]. Circular economy, resource efficiency and sustainability issues are at the centre of the Nexus. As resources are tightly interlinked and the use of one requires the presence of the other (e.g., the production of energy requires water and the production of food requires water and energy), resource use encompasses complex interactions and potential conflicts among Nexus dimensions. This article presents a modelling framework for these interactions, aiming at establishing a methodology for its further analysis. Depending on the number of Nexus dimensions considered, such analysis could become quite complex, even chaotic at times; therefore, a systematic framework that addresses the complexity of interactions within the Nexus is needed.

2. Materials and Methods

In the context of the Horizon 2020 research and innovation project entitled SIM4NEXUS [7] funded by the European Commission, the complex network of interlinkages of five Nexus domains is investigated: Water, Land Use, Food, Energy and Climate. Defining the five Nexus domains reveals the useful aspects taken into account in the analysis and sets the framework on which the analysis is developed.

Water is:

1. The water system, hydrological cycle, habitat for species, aquatic ecosystem, with characteristics such as discharge patterns, water level, morphology of water body, precipitation and evapotranspiration patterns, chemical and ecological quality and aquatic biodiversity.
2. A natural resource, water use for all sorts of human needs, with quantity and quality, emissions, discharges, withdrawal and consumption, water footprint. Water quantity and quality are affected by human use, either on purpose—water management—or as a (negative) side effect.
3. Itself as a geographical phenomenon, including lines (canals and rivers) and surfaces/areas that may be inter-connected and are used for transport and offer room for activities.

Land is:

4. The land and soil system, with its cycles of nutrients and organic matter, habitat for species, terrestrial ecosystems, with characteristics e.g., soil type, slope and terrestrial biodiversity.
5. A natural resource, land use, with quantity and quality intensity and land footprint. Land and soil are affected by human use, either on purpose—land management, agriculture—or as a (negative) side effect, e.g., erosion and degradation, sealing, salinization.
6. Itself as a geographical phenomenon, 'room' for living, acting and transport e.g., urbanization, industrial areas, roads, including spatial planning.

Food is, by definition, a socio-economic domain, with:

7. Food production, primary (agriculture) and secondary (industrial food processing)
8. Food consumption
9. Both food production and consumption are connected through supply chains, trade, markets, prices & price volatility.

Energy is, by definition, a socio-economic domain, with:

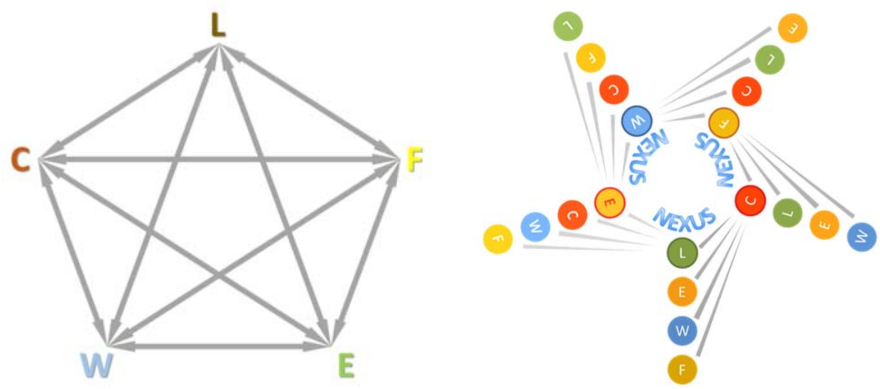
Energy production, primary & mining, secondary e.g., coal into electricity
Energy consumption
Both energy production and consumption are connected through energy transformation from one form to another, supply chains and networks, trade, markets, prices.

Climate is the long-term pattern of the weather. Climate and weather should not be mixed up: There is an actual climate and climate change, the latter being the change in long-term weather patterns. Climate is affected by greenhouse gas (GHG) concentrations in the atmosphere, in its turn influenced by GHG emissions and storage. The other way round, climate change influences all other Nexus components. Climate change is connected to the other nexus components by:

1. Climate change mitigation, reducing the emissions and increasing the storage of greenhouse gases (GHG), expressed as CO_2 equivalents, by water and land management, energy and food production.
2. Adaptation of water and land management, energy and food production to changing long-term weather patterns.

Water, Energy, Food, Land Use and Climate, the five Nexus components are related to one another, through a number of direct and indirect interlinkages (Figure 1a). A direct interlinkage between two components (e.g., Water and Energy) is defined as the effect in a component's status (e.g., Energy), caused by a change in the other component's status (e.g., Water), assuming that the rest of the components (e.g., Food, Land Use or Climate) remain constant and do not interfere with the status of these two components. For this example, a change in Water (ΔW), such as reduced availability of fresh water, will cause a shift in energy (ΔE), by limiting the available cooling water and leading to possible brown-outs or black-outs. This is one of various direct ways that a shift in Water (ΔW) would cause a shift in Energy. This is referred to as the Water-Energy direct interlinkage and is denoted as W→E, or simpler as WE; it comprises all the ways that a change in water, including water quality, quantity, temperature, etc. can affect Energy. It should be noted that each direct interlinkage is unique and the interlinkage of opposite direction is a different one; thus, WE is a different interlinkage to EW. The latter includes the effect that a change in Energy can cause in Water, which is completely different than the opposite. According to this framework, the unique direct interlinkages of the Nexus dimensions sum up to 20. Those 20 interlinkages are presented schematically in Figure 1b and are listed below:

- Water: WF, WC, WL, WE
- Energy: EW, EC, EF, EL
- Land Use: LE, LC, LW, LF
- Climate: CL, CE, CW, CF
- Food: FC, FL, FE, FW



(**a**) (**b**)

Figure 1. (**a**) Nexus component interlinkages, showing all interrelations between different Nexus components; (**b**) Schematic of Nexus component interlinkages, showing how each one of the five Nexus components relate to the other four.

3. Results and Discussion

The direct interlinkages described above are considered as 1st order interlinkages. Except for these twenty direct interlinkages, one Nexus component may also affect another through indirect interlinkages. This means that a change in one Nexus component can cause a change to another component through a change in a third component. To model higher-order interlinkages, three-, four- and five-letter acronyms are used depending on the number of components interacting. For example, to describe the changes caused to Water by an initial change in Food, through the Climate component, the FCW acronym is used. This would be a 2nd order interlinkage. Similarly, Food → Climate → Energy → Water (FCEW) would describe a 3rd order interlinkage and Food → Climate → Energy → Land Use → Water (FCELW) would describe a 4th order interlinkage. An example of the fourth order indirect interlinkage FLWEC would be the following: An increase in Food production would cause a change in Land Use, namely more land would have to be converted to agricultural land. Such a change in Land Use would result to an increase in agricultural Water demand, thus affecting the Water domain. Such a change in Water would cause an increase in Energy demand for pumping; this change would be more pronounced if water comes from groundwater and will increase as pumping depths increase. The Energy change would in turn result in a change in Climate, i.e., an increase in GHG emissions, especially in the case of fossil fuels.

It should be noted that, as described in this FLWEC example, only the linear one-to-one relationships of Nexus components are considered in these higher order interlinkages. Thus, a change in Food would cause changes not only in Land Use (FL in FLWEC), but also in Water (FW), Energy (FE) and/or Climate (FC). However, we do not consider these other Food interlinkages; the effect on Water is *only* considered through Land Use (LW in FLWEC) and similarly the effect on Energy *only* through Water (WE in FLWEC) and the effect on Climate *only* through Energy (EC in FLWEC).

In order to define and record the numerous different influence pathways of different orders, the Nexus tree for one of the Nexus dimensions is designed (Water is used as an example, shown in Figure 2). The Nexus tree is the schematic depiction of all different pathways that lead to various effects caused by a single change in one of the components. An initial single change in the central Nexus dimension causes corresponding changes in the other Nexus components through the branches of the Nexus tree. Specifically, for the Nexus tree for Water shown in Figure 2, we first see all four first-order connections (WC, WE, WF and WL), signifying how a change in Water can affect Climate, Energy, Food and Land Use, respectively. Moving on to the second-order links, we see that three branches are formed out of each one of the four Nexus components (C, E, F and L), since the link with Water has already been taken into account (first-order connection). This way, Climate is linked to Energy, Food and Land Use; Energy is linked to Climate, Food and Land Use; Food is linked to Climate, Energy and Land Use and Land Use is linked to Climate, Energy and Food. As we move out to level 3, the number of branches out of each Nexus component is now two, while at level 4, only one branch forms out of each Nexus component. This way, we ensure that each pathway, when followed from the centre all the way to the end of the tree as it branches out, will not repeat a Nexus component, but will have a unique combination of all five Nexus components. A total of 24 unique combinations are shown in this Nexus tree, which has Water at its centre; these are the following: WCLFE, WCFLE, WCELF, WCLEF, WCFEL, WCEFL, WELFC, WEFLC, WECLF, WELCF, WEFCL, WECFL, WFLEC, WFELC, WFCLE, WFLCE, WFECL, WFCEL, WLFEC, WLEFC, WLCFE, WLFCE, WLECF, WLCEF. Similar Nexus trees can be constructed with the other four Nexus components at their centres, namely, Energy, Land Use, Food and Climate; thus, the total number of unique fourth order interlinkages for the whole Nexus is 24 × 5 = 120.

Following this analysis, it is possible to define all ways through which one Nexus component affects another. In this work, we will show an example for how a change in Water affects Land Use, using the Nexus tree approach: We define all first-, second-, third- and fourth-order interlinkages that have Water as a starting point and Land Use as the final point. This is shown in Figure 3, in which we repeat the Nexus tree shown in Figure 2, having eliminated all pathways that do not involve Land Use. The result is a set of 16 pathways: WL, WEL, WFL, WCL, WEFL, WECL, WFEL, WFCL, WCEL, WCFL, WEFCL, WECFL, WFECL, WFCEL, WCEFL and WCFEL and includes all direct and indirect ways that a change in Water can affect Land Use. When quantitative modelling is conducted and all coupled pathways can actually be quantified, then the total influence that a change in Water will have on Land Use will be the sum of all direct and indirect quantities, as shown below. Naturally, some higher order interlinkages might not be significant and will eventually drop out, allowing for the more significant ones to dominate the total effect that Water has on Land Use. A Table that lists all interlinkages for all Nexus components following the Nexus tree approach is included in the Appendix A.

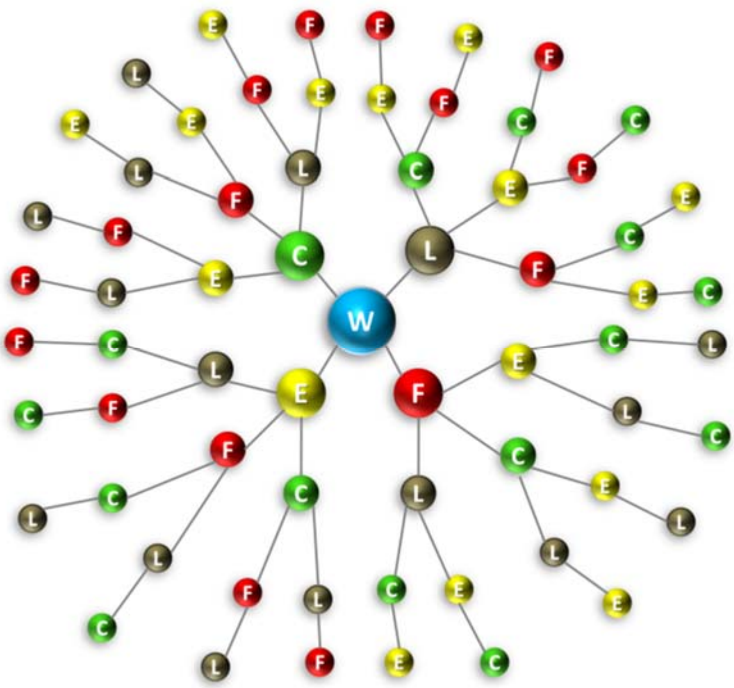
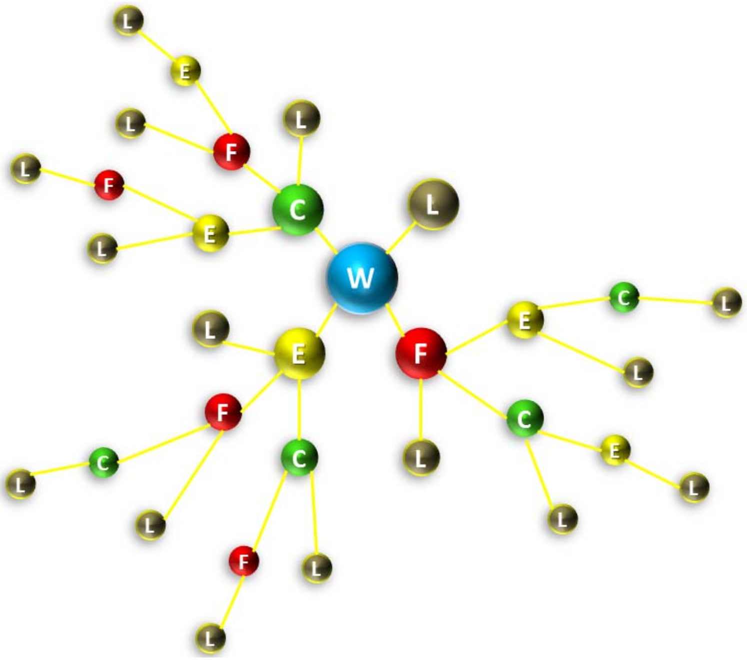


Figure 2. Nexus tree for Water showing the formation of all 24 unique fourth-order interlinkages. Similar trees can be created for all five Nexus dimensions (W, E, F, L, C), creating a total of 120 unique fourth-order interlinkages for the five-dimensional Nexus.



	=	WL	+											1st order
		WEL	+	WFL	+	WCL	+							2nd order
W to L		WEFL	+	WECL	+	WFEL	+	WFCL	+	WCEL	+	WCFL	+	3rd order
		WFLCE	+	WFCLE	+	WFLCE	+	WLCFE	+	WCLFE	+	WCFLE		4th order

Figure 3. Nexus tree for Water to Land Use, showing the formation of all 16 direct and indirect pathways by which a change in Water can bring about a change in Land Use.

The Nexus tree approach creates a depiction of the chain of interlinkages and can be used to guide modellers in a step-by-step approach to systematically assess a simulation without leaving out any direct or indirect interrelation. It outlines the architecture of the Nexus modelling framework, which, at this stage, does not take into account any feedback loops, which could be important, depending on the circumstances. For example, a change in Water drives a corresponding change in Energy (WE), which could in turn drive further change in Water (EW) and another change in Energy and so on. This feedback loop, W → E → W → E → … could lead to changes with a multiplicative effect, magnifying the effects that one Nexus component has on the other, or could dissipate changes, leading to a steady state. Whichever the case might be, the Nexus tree modelling framework presented herein has the limitation of not including such feedback loops; an extensive Nexus modelling framework should definitely include them in the analysis, especially when there is evidence that they are important.

Author Contributions: C.L. conceived the concept of the Nexus tree approach; C.L., D.K. and N.M. worked together to refine it; M.W. contributed in the Materials and Methods, by providing definitions for Nexus components; C.L. wrote the paper with input from D.K. and N.M.; M.W. reviewed the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of 1st, 2nd, 3rd, and 4th degree pathways for all different Nexus interlinkages.

Climate		Energy		Food		Land		Water	
	CW		EW		FW		LW		WL
	CEW		ELW		FLW		LEW		WEL
	CFW		EFW		FCW		LCW		WFL
	CLW		ECW		FEW		LFW		WCL
	CELW		ELFW		FLEW		LECW		WEFL
	CEFW		ELCW		FLCW		LEFW		WECL
	CFEW		ECLW		FCLW		LCEW		WFEL
Climate	CFLW	Energy	ECFW	Food to	FCEW	Land to	LCFW	Water to	WFCL
to Water	CLEW	to Water	EFLW	Water	FECW	Water	LFEW	Land	WCEL
	CLFW		EFCW		FELW		LFCW		WCFL
	CEFLW		ECFLW		FCELW		LCEFW		WFLCE
	CELFW		ECLFW		FCLEW		LCFEW		WFCLE
	CFELW		EFCLW		FECLW		LECFW		WLFCE
	CFLEW		EFLCW		FELCW		LEFCW		WLCFE
	CLFEW		ELCFW		FLCEW		LFCEW		WCLFE
	CLEFW		ELFCW		FLECW		LFECW		WCFLE
	CL		EL		FL		LF		WF
	CEL		EWL		FEL		LEF		WCF
	CFL		EFL		FWL		LWF		WEF
	CWL		ECL		FCL		LCF		WLF
	CEFL		EWFL		FEWL		LEWF		WCEF
	CFEL		EWCL		FECL		LECF		WCLF
	CEWL		EFWL		FCWL		LWEF		WECF
Climate	CFWL	Energy	EFCL	Food to	FCEL	Land to	LWCF	Water to	WELF
to Land	CWEL	to Land	ECWL	Land	FWEL	Food	LCWF	Food	WLEF
	CWFL		ECFL		FWCL		LCEF		WLCF
	CEFWL		EWFCL		FCEWL		LCEWF		WELCF
	CEWFL		EWCFL		FCWEL		LCWEF		WECLF
	CFEWL		EFCWL		FECWL		LECWF		WLECF
	CFWEL		EFWCL		FEWCL		LEWCF		WLCEF
	CWEFL		ECWFL		FWCEL		LWCEF		WCLEF
	CWFEL		ECFWL		FWECL		LWECF		WCELF

Climate to Energy	CE	Energy to Climate	EC	Food to Climate	FC	Land to Climate	LC	Water to Climate	WC
	CFE		ELC		FEC		LEC		WEC
	CWE		EFC		FWC		LWC		WFC
	CLE		EWC		FLC		LFC		WLC
	CFLE		ELFC		FELC		LEWC		WEFC
	CFWE		ELWC		FEWC		LEFC		WELC
	CWLE		EFWC		FWEC		LWEC		WFEC
	CWFE		EFLC		FWLC		LWFC		WFLC
	CLFE		ELFC		FLWC		LFWC		WLEC
	CLWE		ELWC		FLEC		LFEC		WLFC
	CFLWE		ELFWC		FELWC		LEFWC		WELFC
	CFWLE		ELWFC		FEWLC		LEWFC		WEFLC
	CLWFE		EFWLC		FLEWC		LFWEC		WFLEC
	CWLFE		EFLWC		FLWEC		LWEFC		WFELC
	CWFLE		EWFLC		FWLEC		LWFEC		WLEFC
	CLFWE		EWLFC		FWELC		LFEWC		WLFEC
Climate to Food	CF	Energy to Food	EF	Food to Energy	FE	Land to Energy	LE	Water to Energy	WE
	CEF		ELF		FLE		LFE		WFE
	CWF		ECF		FCE		LWE		WCE
	CLF		EWF		FWE		LCE		WLE
	CELF		ELCF		FLCE		LFWE		WFLE
	CEWF		ELWF		FLWE		LFCE		WFCE
	CWEF		ECLF		FCLE		LWCE		WCFE
	CWLF		ECWF		FCWE		LWFE		WCLE
	CELF		EWLF		FWLE		LCFE		WLFE
	CEWF		EWCF		FWCE		LCWE		WLCE
	CEWLF		EWLCF		FCWLE		LCFWE		WFLCE
	CELWF		EWCLF		FCLWE		LCWFE		WFCLE
	CLEWF		ELWCF		FLCWE		LFECW		WLFCE
	CLWEF		ELCWF		FLWCE		LFWCE		WLCFE
	CWLEF		ECWLF		FWLCE		LWCFE		WCLFE
	CWELF		ECLWF		FWCLE		LWFCE		WCFLE

References

1. Brouwer, F.; Giampietro, M.; Anzaldi, G.; Blanko, M.; Bukkens, S.; Castro, B.; Domingo, X.; Fournier, M.; Funtowicz, S.; Kovacic, Z.; et al. The Nexus: Efficient approaches. *Pan Eur. Networks Sci. Technol.* **2017**, *25*, 274–277.
2. Brouwer, F.; Avgerinopoulos, G.; Fazekas, D.; Laspidou, C.; Mercure, J.F.; Pollitt, H.; Pereira Ramos, E.; Howells, M. Energy modelling and the Nexus concept. *Energy Strategy Rev.* **2018**, *19*, 1–6, doi:10.1016/j.esr.2017.10.005.
3. Hoff, H. Understanding the Nexus. In The Water, Energy and Food Security Nexus. In Proceedings of the Bonn 2011 Conference, Bonn, Germany, 16–18 November 2011; Stockholm Environment Institute (SEI): Stockholm, Sweden, 2011.
4. *The Water-Energy-Food Nexus: A New Approach in Support of Food Security and Sustainable Agriculture*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2014. Available online: http://www.fao.org/3/a-bl496e.pdf (accessed on 26 March 2018).
5. Avellan, T.; Roidt, M.; Emmer, A.; von Koerber, J.; Schneider, P.; Raber, W. Making the Water-Soil-Waste Nexus Work: Framing the Boundaries of Resource Flows. *Sustainability* **2017**, *9*, 1881, doi:10.3390/su9101881.
6. Susnik, J.; Chew, C.; Domingo, X.; Mereu, S.; Trabucco, A.; Evans, B.; Vamvakeridou-Lyroudia, L.; Savic, D.A.; Laspidou, C.; Brouwer, F. Multi-Stakeholder Development of a Serious Game to Explore the Water-Energy-Food-Land-Climate Nexus: The SIM4NEXUS Approach. *Water* **2018**, *10*, 139, doi:10.3390/w10020139.
7. SIM4NEXUS. Available online: https://sim4nexus.eu/ (accessed on 30 March 2018).