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TWO-STAGE LAND USE OPTIMIZATION FOR A FOOD-ENERGY-WATER NEXUS SYSTEM: A CASE STUDY IN TEXAS EDWARDS REGION

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Abstract

Efficient land use planning and scheduling in Food-Energy-Water Nexus (FEW-N) related systems is a complicated decision-making problem with resource competitions and conflicting objectives. Systematic thinking based on FEW-N is a necessity for modeling and optimization of the systems. However, challenges arise in making decisions while encountering conflicting objectives, multi-scale and multi-period problems, and multiple stakeholders. To address these challenges, we developed a generic optimization-based land allocation approach, which provides i) a composite FEW-N metric to help solve the multi-objective optimization problem and carry out assessments, and ii) a two-stage decomposition strategy to solve the multi-scale and multi-period planning and scheduling problem. The developed strategy was applied in a case study within the Texas Edwards Region. Computational results indicate that the approach can provide a comprehensive FEW-N metric to select strategies for optimal land allocation and limit stresses in the FEW-N, and achieve trade-off solutions for the multi-scale and multi-period FEW land use systems.

Keywords

Land use optimization, Food-Energy-Water Nexus, multi-period planning,

Introduction

Land use optimization is the result of competitions between different land types (Memmah et al., 2015). The main cause of these competitions are the quantitative constraints of land scales and corresponding Food-Energy-Water (FEW) resources under multiple conflicting objectives (Bergstrom, et al., 2013; Keairns, et al., 2016). FEW resources play a critically important role for sustaining and improving human life, but increasing demands and sustainability

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concerns intensify the competitions between these resources as they become more limited. The coordination of these competitions for achieving an optimal land allocation based on limited FEW resources while promoting efficiencies and sustainability is a complex task. (Miralles-Wilhelm., 2016; Simpson, et al., 2017).

A nexus thinking approach, where FEW flows and interactions are considered in multi-objective land use systems is becoming necessary for the efficient use of FEW resources and trade-off decisions (Garcia, et al., 2016; Ringler, et al., 2013; Avraamidou, et al., 2018a). To identify unbiased decisions and interdependence of FEW elements in different systems, methodologies and tools of current nexus studies mainly include data-intensive modeling for geographical land areas, life cycle analysis for specific technologies or products, and systematic analysis based on descriptive methods (Daher, et al., 2018; Albrecht, et al., 2018). These methods provide essential knowledge and are useful for expanding our understanding of FEW interactions and addressing social and economic concerns of FEW related systems. However, challenges arise in representing quantitative FEW-N interactions in systems that support short systematic land-use decisions while encountering conflict objectives, multiple scales and multiple periods (McCarl, et al., 2017a; McCarl, et al., 2017b).

To address these challenges, we develop a multi-objective optimization approach by considering food and energy production and water use, as multiple objectives for land use systems. The proposed method suggests a two-stage decomposition strategy: (1) In the first stage, models of all the production units are developed by data-driven modeling and global optimization methods based on limited realistic data. FEW flows among them are quantified and interlinked to construct subsystem models, which can be represented as interval superstructures. The small-scale MINLP problems can be solved efficiently due to the limited combinations of land units in the interval subsystems (Nie, et al., 2019); (2) In the second stage, multiple subsystem models with optimal land and FEW allocations are used to construct the extended systematic network and are represented as a larger scale systematic model, which can be solved as a simpler MINLP problem. A series of FEW indices are provided for decision-makers to analysis the FEW-N in the system, carry out quantitative assessment based on different objectives, and achieve trade-off solutions.

The approach is illustrated through a case study on a FEW land use systems within the Texas Edwards Region, showing that the developed approach can provide multiple land allocation planning solutions and can predict corresponding operational schedules for land units within the systems under flexible scales and periods. Computational results from interval models indicate that we achieve optimal operational solutions in the multiple subsystems, and optimal planning solutions of land allocation and extension in the whole system. The performance of these models can be improved by increasing feedback data (Nie, et al., 2018). The systematic model provides an efficient method for extending the land allocation solutions to multiple land scales. For multiple objectives, a proposed FEW metric can be applied to select strategies for optimal land allocation that minimize the FEW-N stresses in the land use system (Avraamidou, et al., 2018b).

Problem Definition

The goal of this work is to provide a multi-period decision-making model that maximizes the trade-off benefits of the FEW-N based land use system. In order to generate a model for the system, the following information is specified: the objectives, the system construction, the production units, the input-output FEW data and Nexus, and the decision variables.

In the FEW-N based land use system, according to the concerns of stakeholders and policy-makers, food production (TF), energy use or production (TE), and water use (TW) are taken as the three optimization objectives.

Figure 1 briefly shows the structure of our land use system. Basically, the system includes three subsystems: crop mix subsystem (C), livestock mix subsystem (L), and energy generation subsystem (E). In the system scale, each subsystem requires a corresponding land type, which are shown as land grids. There are competitions between different land types and within the same land types. In the subsystem scale, the specific land for subsystems also can be split for advanced allocation. For instance, the land grids for crop subsystem can be split and allocated to different crop production units. Similarly, in the livestock and energy subsystems, we can split the land grids for different livestock and energy generator units respectively. Thus, there are also land competitions in the subsystems due to production processes of different production units.

The input-output data in the land use system include input FEW and land budgets, constraints of cost and GHG emissions, and other data for dynamic conditions, such as climate conditions. The aforementioned data is updated yearly for the multi-period planning problem. To model the production units in subsystems, all these data are grouped based on the input-output FEW use and production by different productions units, and the Nexus is defined by quantifying the FEW flow sheets through them. For production units, alternative operation strategies are identified based on data availability.

Based on all the above known data and information, model outputs demonstrate two-stage decisions for processes in the system. In stage 1, land grids are allocated for different production units in each subsystem, and the corresponding optimal operational schedules are identified. In stage 2, optimal land allocations are identified among the three optimal subsystems and then multi-year planning decisions for the system are determined.

Considering all of these settings, we propose a two-stage multi-objective optimization model. The details are explained as below.

Two-stage Decision-making Approaches

In this section, we give an overview of the FEW-Nexus metric approach for the multi-objective problem and the decomposition strategy used for the two-stage decision-making problem.

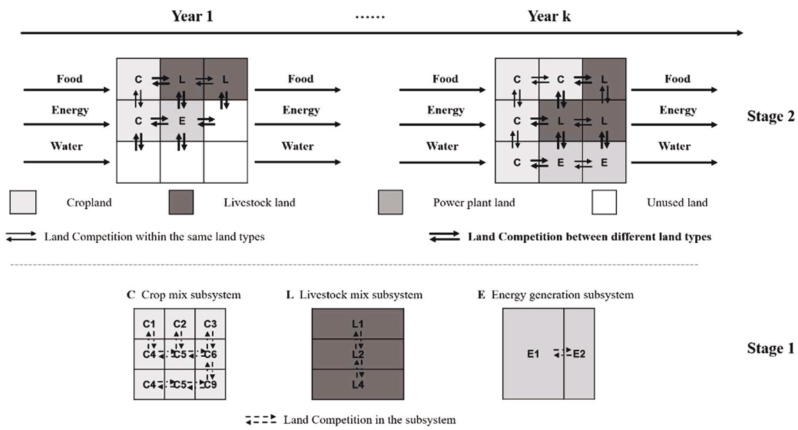

Figure 1. Two-stage land use optimization problem

The FEW-Nexus metric approach for the multi-objective optimization problem

Since the problem has been defined as a multi-objective optimization problem by considering maximum food yield (or minimum food use), minimum energy use (or maximum energy production), and minimum water use, three indexes for them are defined respectively (Eq. (1) – Eq. (5)).

$$F_{sc}^{1} = \frac{TF - TF_{min}}{TF_{max} - TF_{min}} \quad (1)$$

$$F_{sc}^{2} = 1 - \frac{TF - TF_{min}}{TF_{max} - TF_{min}} \quad (2)$$

$$\mathrm{E}_{sc}^{1} = 1 - \frac{\mathrm{TE} - \mathrm{T}\ _{\mathrm{min}}}{\mathrm{TE}_{\mathrm{max}} - \mathrm{TE}_{\mathrm{min}}} \quad (3)$$

$$\mathrm{E}_{sc}^{2} = \frac{\mathrm{TE} - \mathrm{T}\ _{\mathrm{min}}}{\mathrm{TE}_{\mathrm{max}} - \mathrm{TE}_{\mathrm{min}}} \quad (4)$$

$$\mathrm{W}_{sc} = 1 - \frac{\mathrm{TW} - \mathrm{TW}_{\mathrm{min}}}{\mathrm{TW}_{\mathrm{max}} - \mathrm{TW}_{\mathrm{min}}} \quad (5)$$

where F_{sc}^{1} (F_{sc}^{2}), E_{sc}^{1} (E_{sc}^{2}), and W_{sc} are indexes for the FEW objectives TF, TE and TW. For crop and livestock subsystems, F_{sc}^{1} and E_{sc}^{1} are chosen as the indexes for food production and energy use. For the power generation subsystem, F_{sc}^{2} and E_{sc}^{2} are chosen as the indexes for food use and energy production. A FEW-N metric FEWs, is defined to integrate the FEW indexes together, converting the multi-objective optimization problem into a single objective optimization problem (Eq. (6)).

$$\mathrm{FEW_S} = \frac{1}{2}(\mathrm{F_{sc}E_{sc}} + \mathrm{E_{sc}W_{sc}} + \mathrm{W_{sc}F_{sc}}) \sin 120^{o} \quad (6)$$

where $\mathrm{F_{sc}}$ can be F_{sc}^{1} for food yield and F_{sc}^{2} for food use; $\mathrm{E_{sc}}$ can be E_{sc}^{1} for energy use and E_{sc}^{2} for energy production. The metric $\mathrm{FEW_s}$ integrates all the three main indexes of the FEW-N by using them to construct a triangular spider map, presented in Figure 2. Therefore, the objective function of the optimization problem can be simply converted to the maximization of the graph area combined by the three indexes, and the solution can be easily visualized on the spider plot. More information on the metric used can be found in our previous work (Avraamidou, et al., 2018b).

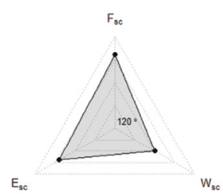

Figure 2. Representation of the FEW metric (F_{sc}: Food index; E_{sc}: Energy index; W_{sc}: Water index)

By using the FEW metrics, a "data processing-modeling-optimization and assessment" framework from previous work will be applied here to construct surrogate models for production units in each subsystem, and solve the multi-objective problem based on the defined objectives and available data (Nie, et al., 2019).

A decomposition strategy for the two-stage decision-making problem

In order to solve the proposed decision-making model, a decomposition strategy is used for solving the multi-period planning and scheduling problem. In particular, we decompose the problem into an operational scheduling problem, comprising only the 1st stage variables and related constraints, and a multi-period planning problem that involves 2nd stage decisions. The optimal solutions for the 1st stage problem will be transferred to the 2nd stage problem as input variables and constraints, and the optimal decisions of 2nd stage problem also will be updated as the initial settings for solving the next year's 1st stage problem. Thus, the multi-period planning and scheduling problem can be solved recursively.

The 1st stage variables refer to decision variables that must be decided for different production units in the subsystems, including the operational schedules, trade-off solutions of input-output FEW resources, and land allocations. Specifically, the objectives for 1st stage problem are the total food production or use (TF), total energy use or production (TE), and total water use (TW) of each subsystem.

For instance, for the crop subsystem in one period T, the objective of maximum total food production is given as below (Eq. (7)).

$$\max TF^{C}(\mathrm{T}) = \sum_{c}\sum_{i}\omega_{c}(F_{ci}(T) - F'_{ci}(T)) \tag{7}$$

$$F_{ci}(T) \leq y_{ci}(T) \times bigM \tag{8}$$

where $c \in \mathrm{C}$ and $i \in \mathrm{I}$ are production units of crop (C) and cropland grids belonging to crop subsystem. F_{ci} is the food yield from production units and F'_{ci} is the food consumed as feedstocks for bioenergy production. The binary variables y_{ci} control the land allocations for different crops in the crop subsystem (Eq. (8)). ω_c is the scaling factors for different crops. The food output F_{ci} can be simulated by the surrogate model $\hat{F}(E, W|S)$ based on the input energy (E), water (W), output food (F) and operational schedules (S) through data-driven modeling methods (Nie, et al., 2019). The budgets of the input-output FEW for production units are taken as constraints of the 1st stage problem. Similarly, the objectives of energy use (TE^C) and water use (TW^C) for the crop subsystem can also be defined. Then, the optimal solution for the subsystem can be achieved by using the FEW-Nexus metric based approach (Eq. (1)-(6)).

The 2nd stage variables refer to decision variables that must be decided for multiple subsystems in the land use system, including the multi-period planning for land allocations and extensions based on FEW supply and demand, available budgets of land, cost and emissions, and other related constraints. The objectives for 2nd stage problem are the total food production (TF), total energy production (TE), and total water use (TW) of the system.

The objective of TF for the 2nd stage is shown as an example (Eq. (9)):

$$\max \mathrm{TF(T)} = \alpha_C(T)\, TF^{C}_{opt}(\mathrm{T}) + \alpha_L(T)\, TF^{L}_{opt}(\mathrm{T}) - \alpha_E(T)\, TF^{E}_{opt}(T) \tag{9}$$

Constraints on land budgets:

$$\alpha_C(T) + \alpha_L(T) + \alpha_E(T) \leq \mathrm{G(T)} \tag{10}$$

Constraints on land conversion:

$$\alpha_C(T+1) + \alpha_L(T+1) + \alpha_E(T+1) - (\alpha_C(T) + \alpha_L(T) + \alpha_E(T)) \leq \beta \tag{11}$$

where the optimal results of subsystems $TF^{C}_{opt}(T), TF^{L}_{opt}(T)$, and $TF^{E}_{opt}(T)$ are updated from the 1st stage solutions. Integer variables $\alpha_C(T), \alpha_L(T)$, and $\alpha_E(T)$ represent the subsystem numbers of the land use system, which are constraint with the yearly land budgets G(T) (Eq. (10)). Similarly, the objectives of energy production (TE) and water use (TW) for the system can also be defined, and the optimal solution for the system in period T can be achieved through the FEW-Nexus metric based approach (Eq. (1)-(6)). The dynamic constraints for multi-period planning including the land conversion constraints (Eq. (11)), economic cost and GHG emissions will be updated for the 1st stage optimization of the next period T+1. Further details of the model design and results are not included in this paper due to space limitations.

Case Study

The proposed methodology is illustrated by a case study for a crop-livestock-energy system in Edward Aquifer Region, Texas. The available data of Bexar County in this region are used. Table 1 summarizes the main conditions for the system, other related conditions include alternative operation techniques, strategies, dynamic climate conditions, and the model size of the system. The system can be extended as more data becomes available.

Table 1. Conditions and model size for the case study

Items	Conditions
Time horizon in 1st Stage	12 months
Time horizon in 2nd stage	5 years
Crop mix subsystem	9 crops
Livestock mix subsystem	3 livestock
Energy generation subsystem	4 types
Land types	4 types
Land grids	9×9
Continuous variables	150,680
Binary variables	18,045
Integer variables	55
Gap	0.001%
Solution time	875 s

Optimal solutions for the 1st stage decisions

The optimal operational decisions for subsystems in one period (year) are solved in the 1st stage. As example results for subsystems, Figure 3 shows the monthly optimal irrigation schedules in one year for the crop mix subsystem, and Figure 4 shows the optimal land allocation and assessment performance from the FEW_S metric. Figure 5 shows the monthly optimal power generation for the power generation subsystem based on the dynamic power demand. Figure 6 is another example of the optimal land allocation and assessment for the power generation subsystem. The radar maps of the proposed FEW_s metric shows that the solutions by maximizing the metric FEW_s can give balanced designs for decision-making in each subsystem.

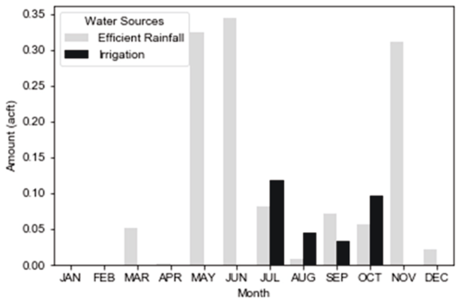

Figure 3. 1st stage decisions in one year: optimal irrigation schedules for the crop mix subsystem

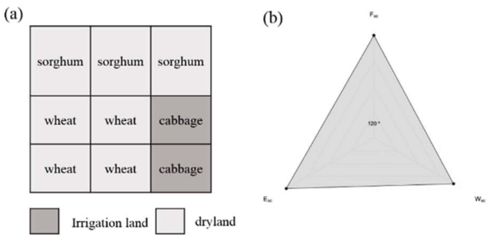

Figure 4. 1st stage decisions in one year: optimal solutions and assessment for the crop mix subsystem. All the land grids have same scales. (a) Optimal land allocation for crop mix; (b) solution assessment based on the FEW metric

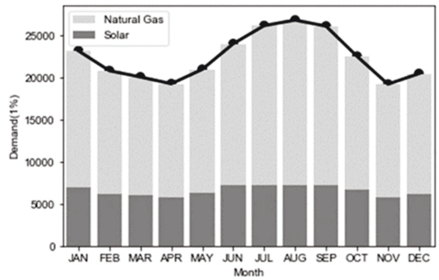

Figure 5. 1st stage decisions in one year: optimal power generation (Black line: Power Demand)

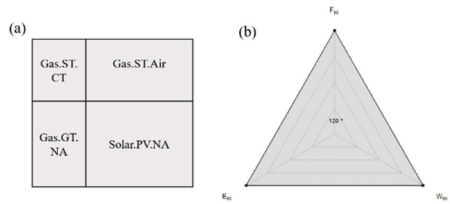

Figure 6. 1st stage decisions in one year: optimal solutions and assessment in the power generation subsystem. (a) Optimal land allocation for power plants. [1] Optimal name capacity: Gas.ST.CT-50 MW, Gas.ST.Air – 100 Capacity, Gas.GT.NA – 50 MW, Solar.PV.NA – 100 MW; (b) solution assessment based on the FEW metric

Optimal solutions for the 2nd stage decisions

In 2nd stage, the planning problem of land allocations and extensions for the system are solved based on the updated results from 1st stage. In this case study, a 5-year planning problem is solved in 2nd stage, and the example results of 1st, 3rd, and 5th year are shown in Figure 7. The performance of the FEW metric show that there is a stable performance when considering FEW Nexus in the system for the multi-period land allocation and extension.

[1] Generation Technique: ST – steam turbine, GT – combustion turbine, PV - photovoltaic; cooling technique: CT – cooling tower, Air – dry cooling, NA – no cooling water

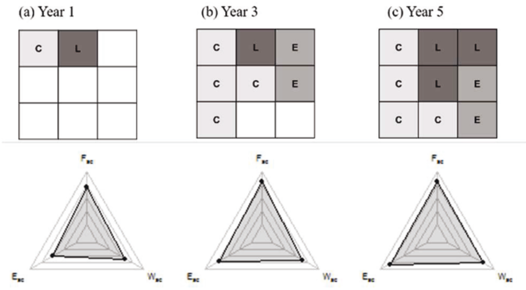

Figure 7. 2nd stage decisions for multi-period: land allocation and extension in the FEW land use systems. (a) Year 1; (b) Year 3; (c) Year 5.

Conclusion

Trade-off land use decisions call for a systematic methodologies and models considering conflicted objectives, multi-scale and multi-period problems. This work takes a crop-livestock-energy system as an instance and illustrates a generic two-stage multi-objective land allocation approach, including methods to achieve multi-objective land use solutions based on a FEW-N metric, and a decomposition strategy to solve the planning and scheduling problem in two stages. Computational results indicate that the proposed approach is capable of suppling the decision makers with different trade-off solutions and incorporate FEW-N interactions.

Acknowledgments

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