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Framework for minimising the impact of regional shocks on global food security using multi-objective ant colony optimisation

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ABSTRACT

A general framework for the identification of optimal strategies for mitigating the impact of regional shocks to the global food production network is introduced. The framework utilises multi-objective ant colony optimisation (ACO) as the optimisation engine and is applicable to production-, demand-, storage- and distribution-focussed mitigation options. A detailed formulation for using trade as the mitigation option is presented and applied to a shock to wheat production in North America for illustrative purposes. Different strategies for improving the performance of the ACO algorithm are also presented and tested. Results indicate that the proposed framework has the potential to identify a range of practical trade mitigation strategies for consideration by decision makers, including trade-offs between the extent to which regional shocks can be mitigated and the degree to which existing trade arrangements have to be modified, as well as the relative importance of various trade agreements and different exporting countries.

Software availability

Name of Software: FORTS-ACO
Developers: Jonathan Schulz, Peter Golding, Sam Kapadia, Stella Naylor
Hardware required: PC or Mac
Program language: FORTRAN
Program size: 7.85 MB
Contact Address: School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, South Australia
Contact E-mail: peter.golding@hotmail.com
Source Code: https://github.com/petergolding/FORTS-ACO
Cost: Free for non-commercial use

1. Introduction

In an increasingly globalised and technologically advanced world, it is deeply concerning that between 2012 and 2014, 805 million people were chronically undernourished (FAO, 2014). While there have been increasing efforts to address the issue of food security, the complex nature of food production, supply and demand has limited the flow of effective information to decision-makers, inhibiting the development of effective policies and procedures that could allow all humans access to their fundamental rights (FAO, 2014).

Much of this complexity stems from the dynamic nature of food security drivers, including population growth, climatic influences, and shocks to the system. In the first half of this century, the world's population is likely to grow to around 9.6 billion (United Nations, 2014), resulting in a 70% increase in global food demand alone (FAO, 2014). According to the US National Research Council (2010), supply-demand systems will be strained at the production side, too, with global average temperatures increasing by up to 11.5 °F (6.3 °C) before 2100. In addition to these long-term food security drivers, short-term, high-impact ‘shocks’ to the global food network, such as natural disasters or war, can have devastating effects on regional crop production (Leclère et al., 2014; Puma et al., 2015).

Enhancing capacity to mitigate the global impact of regional

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shocks to food production can strengthen food security. Broadly speaking, production, demand, storage, and trade-focused options can be explored. Most production-oriented studies assess long-term global and regional food security by linking crop growth models with global climate models and exploring the range of possible management responses to cope with future gradual changes in climate (Balkovič et al., 2014; Deryng et al., 2011; Lu et al., 2013; Tatsumi et al., 2011). These management responses may be limited in the face of extreme impacts. Other production-focussed options include the development of more resilient crops and optimized field-crop allocations (Zabel et al., 2014; Koh et al., 2013). Demand-focussed options include, among others, consumption restrictions and diet change (Jalava et al., 2014). Improvements in food security from production- and demand-focussed approaches will tend to accrue over longer time periods. Storage-focussed options, such as improved storage techniques to prevent loss (Abiodun et al., 2012; Lu et al., 2013; Dejene, 2004), as well as the distribution of stocks (Marchand et al., 2016), have also been investigated, and can have a more immediate impact on mitigating shocks to the food system. Recently, an increasing number of studies have focussed on the distribution side of the global food system, including the evolving robustness of supply networks (Puma et al., 2015) and tele-connected food supply shocks (D'Amour et al., 2016). Production, demand, storage or trade focussed approaches can be considered in isolation or in combination, depending on the desired mitigation strategy. Consequently, the **first objective** of this paper is to introduce a general framework for the identification of optimal strategies for mitigating the impact of shocks to the global food network.

Given that the number of possible combinations of options for mitigating high impact shocks is extremely large at the global scale, the proposed framework incorporates a formal optimisation approach in order to enable optimal or near-optimal mitigation strategies to be identified. It is proposed to use evolutionary or other types of metaheuristic optimisation algorithms for this purpose, as they (i) can be linked with existing simulation models of complex systems (e.g. crop growth models), making them extremely flexible and easy to use (Maier et al., 2014, 2015; García-Martínez et al., 2007), (ii) can deal with discrete decision variable values, which is important when solving many practical problems (Savic and Walters, 1997), (iii) can identify a range of optimal or near-optimal solutions, making them advisory, rather than prescriptive, enabling factors other than those included in the mathematical formulation of the optimisation problem to be considered in selecting the best solution (Maier et al., 2015) and (iv) have been used extensively to solve a wide range of environmental problems (Nicklow et al., 2009; Maier et al., 2014; Afshar et al., 2015). However, a potential limitation of using evolutionary algorithms (EAs) and other metaheuristics is that the computational effort required to identify optimal or near-optimal solutions can become a challenge when dealing with problems with large search spaces, as is often the case when they are applied to real-world problems.

In the past, a number of approaches have been taken to address this issue, including reducing the size of the search space (Zheng et al., 2015; Creaco and Pezzinga, 2015; Li et al., 2015; Bi et al., 2015; Keedwell and Khu, 2006; Lerma et al., 2015; Dorigo and Gambardella, 1997; Afshar, 2008; Foong et al., 2008; Szemis et al., 2012; Nguyen et al., 2016b), starting the search from promising regions in the solutions space (Bi et al., 2015; Lerma et al., 2015; Keedwell and Khu, 2006) and improving algorithm searching ability (Lerma et al., 2015; Afshar, 2008). Ant colony optimisation (ACO) (Dorigo and Gambardella, 1997), which is a metaheuristic based on the foraging behaviour of ants, has been shown to be particularly well-suited to dealing with problems with large search spaces, as they have the ability to dynamically reduce the size of the search space for problems where some decision variable choices are incompatible (Afshar, 2008; Foong et al., 2008; Nguyen et al., 2016b; Szemis et al., 2012) and can improve the speed of convergence by exploiting domain knowledge via a visibility heuristic (Nguyen et al., 2016a). Consequently, ACO is included as the optimisation engine in the proposed framework.

However, while the mechanisms with which ACO can reduce computational efficiency are generic, they have to be tailored to specific applications. Consequently, the **second objective** of this paper is to introduce and test the effectiveness of different approaches to increasing the computational efficiency of ACO for a particular case study for the sake of illustration. The case study considered for this purpose is the determination of the optimal trade response to regional shocks to global food production in order to minimise both direct and indirect food shortages in affected countries. In addition to enabling the proposed optimisation framework to be illustrated and enabling the effectiveness of different approaches to increasing the computational efficiency of ACO to be tested, the case study will also illustrate the potential of the proposed framework to provide insight into the utility of using trade as a strategy for mitigating the global impacts of large regional shocks to wheat production, which is the **third objective** of this paper.

The remainder of this paper is organised as follows. The proposed ACO-based framework for the identification of optimal mitigation strategies to regional shocks to food production (FORTS-ACO) (Objective 1) is introduced in Section 2, including the formulation of the optimisation problem. An adaptation of the general framework introduced in Section 2 to the problem of mitigating the impact of regional shocks to food production via global trade is presented in Section 3 for illustration purposes, including the custom searching operators proposed to improve the computational efficiency and quality of solutions generated by the ACO algorithm (Objective 2). The particular case study to which the formulation introduced in Section 3 is applied (Objective 3) is outlined in Section 4, which considers optimal trade responses to a shock to wheat production applied to North America, and the results of these analyses are presented in Section 5. Finally, a summary and conclusions are presented in Section 6.

2. General optimisation framework

Fig. 1 gives an overview of the proposed framework for the identification of optimal strategies for mitigating the impact of shocks to the global food network (FORTS-ACO). As can be seen, the framework consists of two major steps: the formulation and subsequent solving of the optimisation problem, which are the generic steps used as part of the systems approach (see e.g. Wu et al., 2016). Problem formulation includes the specification of the mitigation options to be investigated, which are the decision variables in this optimisation problem and the specification of the objective function(s) to be optimised, as well as any constraints on the decision variables or solutions. Once the optimisation problem has been formulated, it can be solved using the ACO algorithm. As can be seen in Fig. 1, ACO is used to generate trial solutions (mitigation strategies) by selecting a value of each decision variable using its solution generation mechanisms, the computational efficiency of which can be increased by adopting a variety of strategies, such as dynamically adjusting the size of the search space and guiding solutions to more promising regions of this space based on domain knowledge of the problem under consideration. These solutions are then evaluated in terms of their objective function value(s) and degree of constraint violation, which generally requires input from a simulation model. Information from the evaluation process is then used to generate the next trial solutions using ACO. This