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A Systematic Review of Crop Planning Optimisation Under Climate Change

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Abstract

Optimising the use of natural resources for food production in the context of changing climate is an increasingly important issue. Optimisation techniques have been shown to be remarkably effective for planning problems, and tools regional planners and farmers can use to determine the viability of agricultural land use planning into the future. This paper systematically reviews the recent literature in this area and draws out the key emerging themes: few studies to date have explicitly incorporated climate projections into optimisation models; increased tension for water resources between stakeholders; and various agricultural production systems of complex versions of crop planning. From this review it can be seen that increasing concentration on the use of climate projection models within agriculturally-oriented optimisation processes is a necessity.

Keywords Crop planning · Climate change · Water management · Optimisation · Computational agriculture

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1 Introduction

Sustainable agriculture, under a rapidly changing climate, is challenged by projected decreased water availability and increased global temperatures, as stated by the United Nations (at its 2023 Water Conference), the Organisation for Economic Cooperation and Development (OECD), the latest reports from the Intergovernmental Panel on Climate Change (IPCC), and the World Bank (United Nations 2023; Herold et al. 2021; Field et al. 2014; IPPC 2019; Jiang and Grafton 2012; Qureshi et al. 2018, 2013; Ripple et al. 2021). Given the constraints on available arable land, and the decreasing availability of water due to changes in climate, optimal use of these scarce resources is critical to ensuring adequate food production.

By formulating agricultural production, land and water use as a mathematical model, computational methods of optimisation have been used to help find solutions. The authors' work in this field has been defined by a number of factors:

- The problem is principally one of *crop planning*, in response to the growing need for sustainability in agriculture;
- The focus has been on *irrigated* agriculture;
- The impact of *climate change* has been a driving concern;
- *Climate change* implies that management of diminishing or uncertain resources, particularly *water management* is of critical importance; and
- Competing demands for water dictate methods that consider the *multi-objective* nature of the solutions required.

The goal of this research has been to determine to what extent agriculture can be adapted to climate change by changes in crop selections.

Prior to 2015, a search of the literature for work specifically addressing the problem of optimally planning the growing of crops, given different climate and water conditions, would have returned very few results. As the work in this systematic review shows, there has been a dramatic growth in interest since, in what is a problem of critical importance. This article examines the current state-of-the-art in this area to identify key themes, current responses and identify gaps, providing clarity and direction for future studies in this critical area. It seeks to investigate the following overarching research question: *to what extent has climate change been actively considered in computational modelling of future agricultural practices?*

2 Methodology

A manual literature review was undertaken, using a systematic approach informed by the work of Mohamed Shaffril et al. (2021) and Fan et al. (2022). Reviewed content was analysed using quantitative and qualitative approaches based on Yin (2015) and Krippendorf (2018). This helped to identify key themes and insights.

This systematic review used the Google Scholar search engine, as it captures both open access and subscription journals. It provides a comprehensive representation of the research area, rather than using specific topic journals and databases such as Science Direct or Scopus. A search was conducted on 31 October 2023 using the full-text search query:

"crop planning" AND
("irrigated" OR "irrigation") AND
"climate change" AND

"water management" AND
("multi-objective optimization" OR "multi-objective optimisation" OR "multiobjective optimization" OR "multiobjective optimisation")

This query was devised to select a subset of climate change-related computational crop planning. The search query initially identified 216 works (including duplicate results) from the year 2012 onwards, with an upward trend in results beginning in 2016. Thus, to be considered in the review, research works needed to be:

- published since 2016;
- written in English;
- peer-reviewed or a completed postgraduate thesis;
- related to optimisation principles and crop planning; and
- with the full text available for review.

Duplicate search results were excluded. After applying the inclusion criteria, the original 194 results from 2016 onwards reduced to 84, with the final number per year summarised in Table 1. Of these, five were theses. Given the timing of the search, the total for 2023 is approximately 80% of the expected number for the whole year. This suggests the target area has experienced significant growth in interest over recent years, indicative of the perceived importance of the issues. Note that as a full-text search was performed, many of the 194 works discovered might only mention the search terms incidentally within the main text, and hence were excluded as they were not related to optimisation principles, crop planning or climate change.

To enhance the clarity and coherence in reporting of our findings, the literature was grouped according to two themes: Climate Awareness in Agricultural Decisions, and Water Use. A thematic-based summary of the existing review articles is also presented to complete the picture of the current state of research in this dynamic and evolving domain.

3 Results

In late 2014, shortly before the period covered by this review, Singh (2014) published a review of works addressing conjunctive use of water resources for sustainable irrigated agriculture. Drawing broadly on the literature supporting conjunctive water use, it gave a comprehensive view of issues and methods attempting to improve *sustainability of water resources* under the impact of *climate change*. As such, it identified some of the issues that are the focus of this review:

Table 1 Publications meeting inclusion criteria by year (the total for 2023 only includes papers up to October)

Year	Count
2023	14
2022	12
2021	12
2020	9
2019	14
2018	11
2017	8
2016	4

- "irrigated agriculture is the largest user of all the developed water resources and consumes over 70% of the abstracted freshwater globally" (p. 1689);
- "shrinking water resources" due to "climate change impacts" (p.1688); and
- the need for "integrated use of simulation-optimization models" (p. 1693).

It did not, however, address the competing demands for water and the need for multi-objective solutions they bring. This review addresses this as well as considering the impact of climate change.

3.1 Quantitative Analysis of Articles

Demonstrating increasing interest in the area of water management, the original search retrieved 16 review papers (10 in the last three years), only four of which were within scope, having sufficient focus on crop planning optimisation (two in the last three years). Their findings are compared with the current review in Section 3.4, but are excluded from the percentages presented in the remainder of this section.

Considering the 80 original research works, beyond the anticipated themes (given the survey parameters) of *water resource management* and *cropping patterns*, the most common problems addressed were *irrigation* (34%), *conjunctive water use* (13%) and the related *groundwater management* (13%), and *reservoir operations* (9%). There are overlapping themes within individual publications.

Over half the original research works (59%) adopted genuine *multi-objective optimisation* (in which multiple candidate solutions are generated) while 39% modelled problems as a *single objective* (some including multiple criteria in a weighted sum); just one paper used both optimisation approaches. Thus, despite the search query explicitly identifying *multi-objective optimisation*, many single objective works were retrieved. Figure 1 plots these trends in absolute numbers (left) and as a proportion of the surveyed papers (right), with the publication counts for 2023 estimated by multiplying the number published to the end of October by 1.2. Despite noisy data, the trends suggest increasing use of genuine multi-objective approaches over the review period, implying growing recognition that not all decision maker concerns can be collapsed into a single objective that weights competing goals.

The most common solution techniques were *evolutionary algorithms* (41%), *linear*, *integer* or *mixed-integer programming* (27%), and *fuzzy approaches* (19%), with temporal trends shown in Fig. 2. Again, the estimated 2023 totals are obtained by scaling observed counts proportionally to the time covered. The trends suggest growth in population-based approaches (evolutionary algorithms) that intrinsically support multi-objective decision-making by operating on a collection of trade-off solutions.

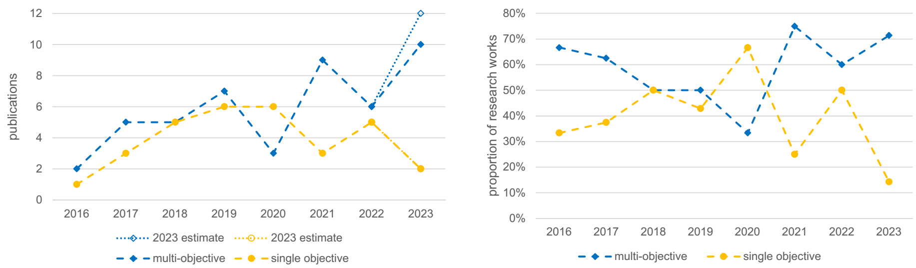

Fig. 1 Prevalence of multi- versus single-objective optimisation approaches

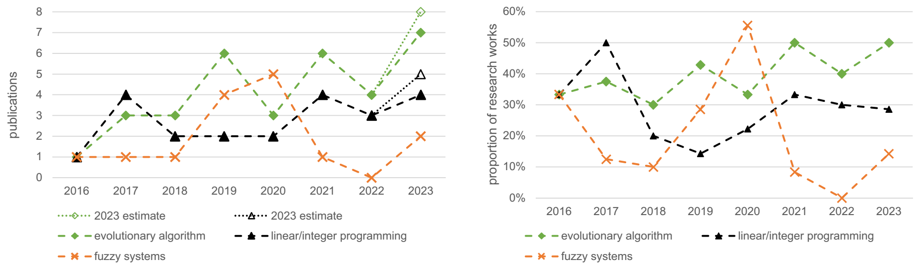

Fig. 2 Prevalence of different solution techniques

Climate change and climate projections were actively considered in only 15% of the original research works, discussed in Section 3.2.1 (some further works acknowledged that climate change will impact on agriculture but did not use projections in their modelling), while 13% concerned *arid/semi-arid regions*, which will be the most severely impacted by reduction in water availability.

3.1.1 Objectives and Decision Variables

Of the 80 original research publications surveyed, 77 (96%) explicitly applied optimisation approaches (as opposed to modelling and prediction to assist decisions makers). Within these 77, the most common optimisation objectives (goals) were *maximising revenue*[1] (92%), *minimising water use* (66%), *maximising crop yield* (42%, which is related, but not identical, to revenue), *protecting the environment* (12%), and *meeting demand* (for crops, water or power, 5%), with 18% exhibiting a mix of other goals outside these categories. Figure 3 illustrates some of the overlaps between the optimisation goals of maximising *revenue or yield* (combined, as these are very similar), reducing *water use*, protecting the *environment*, and *meeting demand*. The area of each set is scaled in proportion to its cardinality, while the overlapping regions are not. Notably, when dealt with as an optimisation problem, reducing water use and protecting the environment were *always* paired with the goal of maximising revenue or yield. This does not make either a redundant goal, of course, as increasing revenue while decreasing water consumption or improving environmental outcomes are often orthogonal (competing) objectives.

Table 2 summarises the most common decision variables in optimisation models developed across the research works, which indicate which component of the problem is controlled/adjusted to achieve a given outcome. The majority (74%) control the *area allocated to crops*, either in aggregate or by directly allocating crops to parcels of land. This allows either the relative proportion of a fixed set of crops to be adjusted or, in fewer works, for identifying candidate changes in which crops are grown (a topic explored in Section 3.3.1). Comparatively few problems were modelled as the *allocation of water* to predetermined uses (agriculture, industry, human consumption), with fewer still controlling *reservoir operations*[2] or *selecting the source of water*.

[1] This is the profit that farmers make by selling their crops.

[2] The original search query retrieved a large number of works concerning reservoir operations, but those that did not also actively consider crop planning were excluded from the survey.

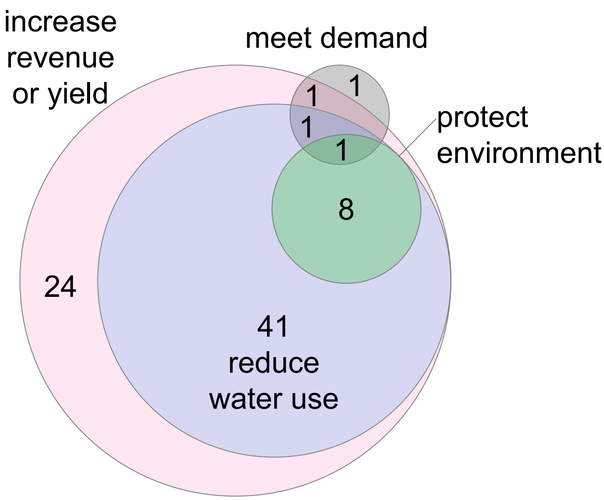

Fig. 3 Frequencies of most common optimisation goals

3.1.2 Target Region

Many of the surveyed publications used case study data for specific regions, illustrated in Fig. 4. In almost all of these, the case study region was near the authors' respective institutions (either same country or, often, same region within it.) The case studies are dominated by East Asia (particularly China), South Asia (particularly India) and West Asia (particularly Iran), accounting for 68% of the publications with a region-specific case study. Australasia, North East Africa and North America appear as case study regions in a further 16%. In many of these regions, the degree of food security is largely determined by domestic agricultural production. It may be noted that the last three contain large arid/semi-arid regions.

3.2 Climate Awareness in Agricultural Decisions

The key issue that research in the area of sustainable and responsive crop planning has faced is the incorporation of climate change projections within their optimisation models and solvers. As such, even though the issue of climate change has been in consideration for decades, within the parameters of the search criteria no articles were returned prior to 2016. There are various degrees of climate awareness, and the remainder of this section is organised accordingly.

Table 2 Most common decision variables in optimisation models

Decision variables	Used in
Allocating area to crops	60%
Allocating crops to parcels of land	14%
Allocating water to areas or users	14%
Reservoir operations (typically release schedules)	3%
Source of water	2%

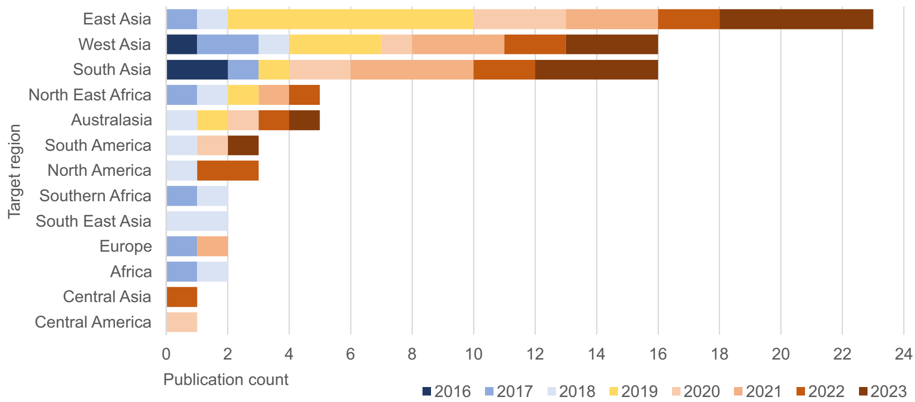

Fig. 4 Frequency of different case study regions across the publications

3.2.1 Active Use of Climate Projections

Despite the world's focus on climate change and need to take action to address it over the coming decades, only a relatively small part of the literature surveyed actively incorporates future climate projections into their modelling and experimental work. For those researchers that did, a number of themes emerged, in particular the issue of water scarcity and water efficiency, as noted by Adly et al. (2018); Hashemi et al. (2019); Khorshidi et al. (2019); Lewis et al. (2019); Li et al. (2019); Zhang et al. (2023). These articles spoke of the difficulties for high yield and high profit crops and their large water requirements, with *climate models predicting less water availability in many areas*. All indicated the need for more water-wise planting. Similarly, the need for effective irrigation was raised (Li et al. 2017; Khorshidi et al. 2019) as also being a way to address this, as well as to ensure investment future-proofing.

Some of the articles (Randall et al. 2020; Mandal et al. 2021; Lewis et al. 2023) described the mechanics of making crop selections while considering changing climate conditions. These presented trade-off surfaces allowing decision makers to determine what cropping patterns will be effective in the future, considering the amount of water that will be required and available at these times. Indeed, Randall et al. (2022); Lewis et al. (2023) took the use of climate projections further in the planning algorithms, by allowing their solvers to consider multiple climate projections simultaneously to achieve solutions robust to climate uncertainty. These allowed for more effective long term predictive modelling. For all the articles that consider active use of climate projection, only Lewis et al. (2019); Randall et al. (2020, 2022); Lewis et al. (2023) evaluated the effect that climate change would have on conjunctive water use for environmental and agricultural needs.

In summary, all articles found significant changes to current practices in irrigated agriculture will be necessary for sustainable agricultural production under the impacts of future climate changes.

3.2.2 Indirect Consideration of Climate Change

It may not always be possible to incorporate sophisticated climate change considerations, or researchers may need to devise an incremental set of work to fully achieve this. Several papers considered the problems of climate change "indirectly" by characterising future scenarios largely based on historical data, responding to potential, future water scarcity mainly by considering the water needs of particular crops in their study regions (Montgomery et al. 2018; Abdelkader and Elshorbagy 2021; Fan et al. 2021; Honar et al. 2021). While there appeared an awareness of the potential impact of climate change, through changing water availability, the studies relied heavily on the past to inform crop planning decisions in the future with the exception of Fan et al. (2021) who relied on external data sources for predicted future water resources.

Dou et al. (2022) also used representative climate scenarios but in addition considered the ecological benefit of effective water use, as did Montgomery et al. (2018) who had an explicit objective of maintaining river flows for environmental purposes.

3.2.3 Climate Extendable Work

For some works, the potential to integrate climate awareness is greater than currently achieved. These papers, while to some extent acknowledging that climate changes may have an impact on current practices, have largely deferred their active consideration to "future study".

Galán-Martín et al. (2017) described a sustainable food production system under current conditions. While commenting on the sensitivity of their results to variations in climate, no data on future climate conditions were incorporated in their study. The risk of climate change on crop yield (specifically maize) was investigated by Kropp et al. (2022) using historical data to potentially increase yields, albeit with a loss in water use efficiency. Begam et al. (2023) considers a problem of maximising net revenue while minimising water requirements, explicitly acknowledging the multi-objective nature of the problem and focussing on solution methods to ensure food security. These articles were primarily concerned with the potential for future difficulties ensuring food security, largely as a result of population increase, though Begam et al. (2023) did consider climate change a relevant challenge.

3.3 Water Use

Water plays a vital role for all crop planning activities. Given the importance of water management, there are a large number of articles for which this is the primary concern. The trade-offs between hydropower generation and crop production are also discussed as they are a major concern in a growing body of literature.

3.3.1 Land use Change and Water Resource Management

Water use has changed significantly over past decades. Agricultural land use has been impacted by reductions in water from increasing alternative applications, which has necessitated decisions on land use to maximise national food security and economic returns. Freshwater availability has remained constant, or in some regions declined; its use for direct human consumption or industrial use has rapidly increased with increasing populations. Apart from Chaloob (2016); Daghighi et al. (2017); Multsch et al. (2017); Liu and Li (2018); Niu et al. (2019); Song et al. (2019); Zhang et al. (2019); Dai et al. (2021); Fan et al. (2021); Shabanzadeh-Khoshrody et al. (2023), the major focus of 58 of the 68 articles that are associated with this issue was having objectives that would maximise revenue of optimised crop plantings and configurations. This is in stark contrast to a lot fewer articles that incorporated environmental needs into consideration (Pastori et al. 2017; Kropp 2018; Niu et al. 2019;

Roje et al. 2020; Ragkos and Ambas 2021; Mohammadzadeh et al. 2022; Moriasi et al. 2022; Sajith et al. 2022) or which determined methods to ensure ongoing food security (El-Gafy et al. 2017; Liu and Li 2018; Kropp 2018; Fanuel and Mushi 2018; Cui et al. 2019; Ren et al. 2019; Roje et al. 2020; Begam et al. 2023; Talukdar et al. 2023; Sabale and Jose 2022; Jain et al. 2023). There is a large overlap between all three groups, which indicates that there will always be a trade-off between economics, the environment, and ensuring that adequate food supplies are available now and into the future.

Changes in climate have meant that water availability patterns have shifted in many parts of the world. In many traditional crop producing areas, water for agricultural use has become a scarce commodity. Several authors explored new efficiencies in water practices, including approaches utilising changes in water use policy, or at the macro level of water resource management (for example, Fowler et al. (2016); Kuschel-Otárola et al. (2018); Sepahvand et al. (2019); Varade and Patel (2019); Chen et al. (2020); Liu et al. (2021); Masood et al. (2021); Upadhyaya and Upadhyaya (2021); Yazdian et al. (2021); Shafa et al. (2023); Luo et al. (2023)). Optimising irrigation systems is seen as an ongoing way of preserving water resources (Chaloob 2016; Singh 2016; Li et al. 2017; Pastori et al. 2017; Multsch et al. 2017; Liu and Li 2018; Juwono et al. 2018a, b; Kropp 2018; Song et al. 2019; Zhang et al. 2019; Ren and Zhang 2019; Ren et al. 2019; Cervantes-Gaxiola et al. 2020; Gurav and Regulwar 2020; Rezaei and Safavi 2020; Roje et al. 2020; Yue et al. 2020; Nanda et al. 2021; Mirzaei et al. 2022; Sabale and Jose 2022; Gong et al. 2023; Liu et al. 2022; Cheng et al. 2023; Kousar et al. 2023; Santos 2023; Yang et al. 2023). Complementary to that has been a move to investigate more water-wise crops (Chaloob 2016; Li et al. 2017; Ikudayisi 2017; Ikudayisi et al. 2018; Daghighi et al. 2017; Gong et al. 2020; Jha et al. 2020; Roje et al. 2020; Dai et al. 2021; Sabale and Jose 2022; Mohammadzadeh et al. 2022; Liu et al. 2022; Huang et al. 2023; Jain et al. 2023; Shabanzadeh-Khoshrody et al. 2023).

The preservation and optimal use of precious freshwater resources is the paramount theme across the works considered here. This topic will become increasingly important with shifting patterns of water availability that occur over time because of the effects of climate change.

3.3.2 Reservoir Operations and Hydropower

An interesting observation from the search process was that the importance of reservoir operations, in connection to crop planning, has increased over the time period of this study. This has often led to competition with agricultural production where reservoirs are used as water stores for the generation of hydropower. A number of publications were retrieved with the original search query in which hydropower was the main focus, with only incidental consideration of downstream activities such as agriculture; these were consequently excluded from the review.

All of the remaining articles (Bou-Fakhreddine 2018; Allam and Eltahir 2019; Dariane et al. 2021; Zhou et al. 2022) considered the tension between using reservoir water resources for hydropower generation and having sufficient water to maintain downstream agricultural practices. This was largely viewed from the perspective of prioritising power generation and determining water-wise crops that could still be grown (Allam and Eltahir 2019; Zhou et al. 2022). The effectiveness of irrigation methods, given the potential limitations of reservoir water availability, were examined by Bou-Fakhreddine (2018) and Zhou et al. (2022). Overall, the balance between power generation and crop planning is a highly complex and evolving socio-economic, eco-technological issue. Increased use of optimisation tools can aid in achieving appropriate balances in different regions.

3.4 Previous Reviews

This review reports on four other review papers that matched the inclusion criteria given in Section 2. These papers can be classified according to a known taxonomy of systematic reviews presented in Fan et al. (2022) and then contrasted against the review presented in this article.

Both Saranya and Amudha (2016) and Kumar and Yadav (2022) are examples of narrative reviews. These are considered to employ an informal review process, with the focus being on theory development. Like this review, Fanuel et al. (2018) and Mellaku and Sebsibe (2022) are examples of systematic reviews – these identify, from the available evidence, which articles in the literature are to be analysed to answer a specific research question.

Fanuel et al. (2018); Kumar and Yadav (2022) and Saranya and Amudha (2016) are primarily concerned with issues of water management in crop production, particularly examining those parts of the literature that are about improving irrigation techniques. Kumar and Yadav (2022), however, reviewed the optimisation techniques. Their article was designed to assist researchers in identifying which optimisation technique to apply to hydrology problems.

The review in this article is broader in scope than these four articles, and is oriented to the issues of climate change. This review focusses on irrigated agricultural land use, informed by future climate predictions due to the pressing concerns regarding agriculture highlighted in Section 1.

4 Discussion

The aim of this systematic review is to document research which considers climate change as an integral component of various crop planning optimisation problems.

This review has highlighted current research is falling short in solving pressing real world problems. Although there is considerable research applying heuristics to bi- and multi-objective problems, relatively few (11) considered predicted climate, by using established climate change models (see Section 3.2.1). Several works focussed on testing mathematical models using historic climate data, but with no comparison of model outputs against historic outcomes, a common failing (Rötter et al. 2011). While the number of papers specifically considering land use is large, an unexpected result has been the nexus of crop planning and hydropower. This indicates a growing desire for low carbon energy to satisfy increasing demand, while concurrently satisfying downstream needs, primarily agricultural water requirements. An identified gap is consideration of environmental water objectives. Overwhelmingly researchers take a human-centric approach to the problem, seeking optimisation of resources to their benefit without due consideration of the natural environment. Only nine papers (12% of those applying optimisation techniques) explicitly include the environment as an optimisation objective.

Optimisation of agricultural land is a sovereign concern globally, focussed on farm-level production optimisation, contributing to gross domestic product and domestic food security. This review found that managing scarce water resources to prepare for future climatic change effects was an emerging concern. However, only two papers took a national approach (Adly et al. 2018; Pastori et al. 2017). The overwhelming majority of research investigates this problem at the regional or basin scale, which is often appropriate to capture the complexity of natural resource interactions and trade-offs.

The tools of optimisation are broad, from mathematical to fuzzy logic; however, evolutionary algorithms emerged as the tool of choice. These approaches permit the large numbers of variables and decision parameters required to represent complex agro-ecosystems and reservoir-hydropower operations.

5 Conclusions

Sustainable cropping practices over time in a changing climate is a pressing issue for societies across the world. Research based on mathematical modelling and optimisation can help with planning and managing increasingly limited resources in the decades to come. The literature reviewed here has shown that variations of the crop planning problem have been formulated for different crops across the world, usually with the aim of maximising revenue, while respecting water availability constraints (primarily from an economic perspective). Many of these have only had a light treatment of climate change issues, or none at all. *Only 12% of the articles reviewed sought to address directly the impact of climate change on agriculture*. Note that while the search strategy produced a large number of matching results, it is possible that some works were not included because of indexation issues or use of alternative terms. However, due to the size and comprehensive nature of the review, it can be concluded with a high degree of confidence that most significant themes have been considered.

There are a few emerging techniques that are able to actively consider climate-predictive models within optimisation processes. These models generally point to a hotter and drier future, requiring current cropping practices to be re-evaluated. There is a tension between land use for urban and industrial purposes, as opposed to agriculture, with competing demands for freshwater given the growing need for drinking supplies and hydropower generation. These issues significantly affect agricultural production for growing populations.

It is evident that there are still gaps which need addressing, and opportunities to be taken, to create inclusive responses to future natural resource trade-offs. More realistic climate change and water resource aspects need to be modelled. In terms of the former, the active incorporation of climate change model data into optimisation approaches is a priority. Also, enhanced optimisation models need to be developed that can ensure that sufficient water is available for agricultural needs, while ensuring electricity demands can be met into the future. In terms of agricultural concerns, modelling, and performing empirical studies on, how farmers implement crop rotational sequences in the context of climate-driven change in water availability and modelling pest and disease impacts will ensure that an optimiser's recommendations will be practicable. More realistic outcomes will highlight potential effects of climate change on commercial food production aspects such as yield, quantity and changing nutritional values.

Author Contributions Marcus Randall, James Montgomery and Andrew Lewis had the idea for this review article. All authors performed the literature search and data analysis. Additionally, all authors drafted and critically revised the work.

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Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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