A Life Cycle Assessment of Guar Agriculture

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Abstract

Guar gum, the main product of the guar crop, is used widely in the US as an emulsifier in the food industry and as fracturing fluid additive in the oil and gas industry. The US is the number one global importer of guar, and interest has grown to domestically cultivate guar in the US. Guar is an annual desert legume native to India and Pakistan. The goal of this study was to evaluate the environmental sustainability of growing guar in the U.S. via a life cycle analysis (LCA). The LCA helps identify the information gap for US agriculture and guide future field studies to optimize guar cultivation in the US.

This study concluded that in terms of environmental sustainability, irrigation, harvesting, and P-fertilization methods offer the most opportunity for improved guar agricultural sustainability. This is promising because one of guar's prominent characteristics is its high water use efficiency and ability to grow in marginal soils. Lowering irrigation and water use can be implemented with simple management practice changes like optimizing irrigation. In addition, this study shows that there is an opportunity for field trials to optimize fertilizer application rates to achieve the greatest yields. This study also found a knowledge gap with respect to C soil fluxes and field emissions of N and P from guar agriculture. As the United States pursues adopting guar agriculture in the Southwest, it will be critical to evaluate irrigation to achieve maximum yields (e.g. drip, flood, sprinkler) and fill fertilizer and emissions knowledge gaps.

Introduction

Guar (*Cyamopsis tetragonoloba*) is an annual desert legume crop shown in Fig. 1 that is native to subtropical and semi-arid regions of India and Pakistan. Its main product, guar gum, is the source of a polysaccharide emulsifier that is used mainly in the food industry (Mudgil, Barak et al. 2014). It is also used in the oil and gas industry: as a gelling agent in oil well stimulation, as an emulsifier in mud drilling, and as an additive in fracturing fluids (Kargbo, Wilhelm et al. 2010, Lester, Yacob et al. 2014). The co-products for guar are guar meal, used in animal feed and guar bagasse, which has the potential to produce biofuels and other high value co-products.

The continual rise of US hydraulic fracturing and the expansion of shale oil gas hydraulic fracturing to new countries like China and Russia has significantly increased the world market demand for processed guar (Singh 2014). The compound annual growth rate of the guar gum market is projected to increase by 7.9% from 2017 to 2022, reaching a value of 1.15 billion USD (MarketsAndMarkets 2017). This global surge has resulted in an unmet domestic demand for guar products and co-products in the US (Singla 2016).

While guar gum drives the market for guar agricultural production, guar co-products also have value and their markets are emerging. Guar meal is a stand-alone animal food supplement because of its high protein levels, about 480 grams of crude protein/ kg of dry matter, similar to soybean meal(Rama Rao, Prakash et al. 2014). Its unique characteristics also allow it to be a binder for other stockfeeds (Bryceson 2004). Guar bagasse is currently being characterized by researchers to evaluate its potential to use in the production of renewable biofuels, which would alleviate our continued dependence on oil and natural gas, a relatively high carbon energy source (Kuhns 2018).

About 90% of guar is produced in India and Pakistan. The U.S. is the number one global importer of guar, and imports 80% of its guar (gum) from India (Singh 2014). Guar can be grown in the US, which offers the opportunity to develop a sustainable bioeconomy in the Southwestern United States. Guar's nitrogen fixing capabilities, high water use efficiency, and low moisture storage requirements make it an ideal crop to be grown in the Southwest US semi-arid to arid conditions, characterized by a lack of available water (Arayangkcon, Schomberg et al. 1990, Mudgil, Barak et al. 2014).

As we begin to cultivate a new industrial crop in the US, there are significant opportunities to enhance the sustainability and yield of guar gum and support its economic advantages for Southwest US. Thus, in order to guide the growth of guar and its products down a sustainable path, we must quantitatively assess the environmental impacts for the production of guar gum and its co-products. This new bioeconomy in the Southwest could have multiple benefits; providing a more reliable and sustainable source of domestic guar that can potentially produce biofuels and other high value co-products while benefiting the regional economy and local rural communities.

There are next to no guar sustainability studies in the literature, and there is a paucity in the literature of guar agricultural practices. The sustainability studies of guar include a comparative LCA of different guar farms grown in the Mediterranean region (Gresta, De Luca et al. 2014), an input-output analysis of guar grown in Turkey (Gokdogan, Seydosoglu et al. 2017), and an energy use study of arid agricultural practices in India (H. Singh 2002). This paper addresses these gaps in literature by conducting an environmental sustainability study of guar agriculture in the Southwest US using life cycle analysis (LCA) methodologies and makes recommendations for data needed to guide sustainable guar production in the US. This study also identifies the greatest opportunity for improvement in regard to environmental sustainability for guar agriculture in the US.

Methods

This LCA follows the framework established by the International Organization for Standardization (ISO) 14040 series (ISO 2006). The LCA methodology is described following the 4 steps of an ISO LCA including 1) goal, scope and system boundary definition, 2) life-cycle inventory data collection process, 3) life-cycle impact assessment, and 4) interpretation. This research also conducts sensitivity and scenario analyses.

2.1 Goal & Scope & System boundary

A cradle-to-gate LCA was completed for the guar agricultural processes in the U.S. The main system of interest in this study was the agricultural processes of guar therefore the functional unit was defined as 1 hectare (ha) of guar bean grown in the U.S. The yields are also given so that the reader can convert impacts to the guar bean, for use in subsequent guar product LCAs.

The system boundary for the LCA of this study is illustrated in Fig. 2. The cradle-to-gate processes within the system boundary of guar agriculture included tillage, pesticide use, fertilizer use, fuel consumption associated with farm equipment operations, and fuel consumption associated with transport of product from field to processing. The only output within the system boundary for this study is guar bean (yield of crop from field). Because of this study's narrow focus on guar agriculture and direct emission sources the system boundary is designated a scope 1, therefore no allocation of impacts is needed for this analysis of the agricultural processes. The edge of the boundary is farmgate and does not include the processing of materials past the farmgate, which is best-practice for an agricultural LCA to simplify analysis (Caffrey and Veal 2013).

2.2 Life cycle inventory (LCI)

Because guar is a new crop in the US, there are no USDA or agricultural databases from which to construct an inventory. Thus, the life cycle inventory data was collected from published peer-reviewed articles; **Table 1** shows the summary of the data used in this LCA, the detailed sources and references are given in Supporting Information (Table A.1). All of the agricultural inputs were derived from experimental field trials from around the globe; none of which are from the US. Irrigation for guar is primarily conducted via sprinkler systems (Gresta, De Luca et al. 2014, Gokdogan, Seydosoglu et al. 2017). None of the studies using nitrogen fertilizers specified the exact type used, therefore urea was assumed to be used in all the studies because it is one of the most common forms of N fertilizer and has the highest percentage of nitrogen. Similarly, the studies using phosphorus fertilizer did not specify exact types except for one study that used phosphorus pentoxide (P_2O_5) (Tripp 1982). Thus, P_2O_5 was assumed to be used for all studies. Of the four studies that used herbicides, two of them used glyphosate (i.e. roundup), the other two used were pendimethalin and Most Micro. Since glyphosate was available in ecoinvent and used in greatest quantities, it was used in this LCA (Gresta, De Luca et al. 2014). Harvesting is commonly conducted using a custom combine harvester (Trostle 2013), while tillage was modeled using harrowing (Gresta, De Luca et al. 2014, Singla 2016). This study also included transportation from the field to the processing facility, estimated in Table 1 using google maps. Transportation was estimated using the distance from Guar Resources, a guar processing facility in Brownfield, TX to the closest known guar field.

Table 1. Summary of guar agricultural data from literature.

Mean values were used as inputs in this LCI.

Agriculture Inputs	min	mean	max	units
Herbicide	2.5	4.375	6.25	kg/ha
Traditional seeder		19.75		kg/ha
N-fertilizer	0	54.86	120	kg/ha
Irrigation	316.8	1405.6	2300	m^3/ha
Transportation		16.09		km
P-Fertilizer	22.41	89.13	200	kg/ha
Biomass Yield	0.44	2.49	7.84	tons/ha

The inputs in Table 2 were matched to an ecoinvent v 3.4 or USLCI unit process. Upstream processes were collected from the ecoinvent database (version 3.4 cutoff) for agricultural inputs. The USLCI (2016) was used for the transportation because of its ability to use data specific to the Southwestern United States, which was the focus area for this study. These databases were used because of their robust nature, including consistent and coherent LCI datasets for various activities which support the credibility and acceptance of the LCA results (Weidema, Thrane et al. 2008). The Rest-of-World designation in the ecoinvent database was used, since US designations were not available. To date, the guar agricultural studies have not evaluated environmental outputs from fields, such as water quality of runoff, dust created during soil management, or soil carbon fluxes. Thus, no field emissions were included in this study.

Table 2. LCI database unit processes used in model

E = ecoinvent v 3.4 cutoff, U = USLCI

Unit process	Database	Process name
Tillage	E	Tillage, harrowing, by rotary harrow
Herbicide	E	glyphosate production
Seeding	E	sowing | Traditional seeder
N Fertilizer	E	urea production, as N
Irrigation	E	Sprinkler irrigation
Harvesting	E	combine harvesting
P-Fertilizer	E	single superphosphate production | phosphate fertilizer, as P2O5
Transportation	U	transport, single unit truck, diesel powered

The yields were compiled from all previous guar literature studies so that the reader can convert impacts from the functional unit used herein (ha) to the guar bean and guar gum for use in subsequent guar product LCAs. Yield used in the analysis represents total guar biomass harvested yield. The biomass yield was used to calculate the environmental impacts of transportation, multiplying the yield (tons) by distance (km). The yield data can be seen in Table A.1. Typically, about 1/3 of the bean weight is endosperm used for guar gum production and the remaining 2/3 is the germ and hull used for guar meal production (Abidi, Liyanage et al. 2015).

2.3 Life cycle impact assessment (LCIA)

The Tool for reduction and Assessment of Chemical and other environmental Impacts (TRACI 2.1) life cycle impact assessment (LCIA) method was used to evaluate seven environmental impacts (acidification, ecotoxicity, eutrophication, global warming, ozone depletion, photochemical ozone formation, and resource depletion) and three human health impacts (carcinogenics, non-carcinogenics, and respiratory effects). This method was developed by the U.S. Environmental Protection Agency and was used because the methodologies used to develop TRACI are the best-available practices for life cycle impact assessment in the United States (Bare 2011).

2.4 Sensitivity Analysis & Scenario Analysis

In order to identify relevant areas to conduct scenario analysis, a sensitivity analysis was completed and data availability limitations were considered. For the sensitivity analysis, a what-if table method was used in excel to analyze the sensitivity of the TRACI environmental and human health impacts to all the inputs, comparing the baseline inputs (i.e. averages from literature) to 80% and 120% of the input values. Subsequently, two scenario analyses were conducted based on the sensitivity analysis and data availability concerns noted during the LCI. The first scenario focused on irrigation, where minimum and maximum literature values were compared to the baseline average of literature values. Another scenario investigated nitrogen fertilizer unit process selection, where the baseline nitrogen fertilizer, urea, was compared to monoammonium phosphate (a source of N & P), calcium ammonium nitrate, and ammonium nitrate, common fertilizers used in agriculture (Table A.2).

Results And Discussion

Irrigation, harvesting, and P- fertilization contributed the most to the life-cycle environmental impacts of guar agriculture (Fig. 3). Irrigation may offer the most room for improvement of the life-cycle environmental impacts. Research shows that efficient irrigation can also improve yields (Alexander 1988).

The irrigation process has the highest impact in 8 of the 10 impact categories (between 27% and 53%) excluding photochemical ozone formation and respiratory effects. Irrigation impacts are highest in the human health carcinogenic, human health non-carcinogenic, and ecotoxicity categories. Chromium VI emissions to water (74%), zinc emissions to soil (44%) and copper ion emissions to water (45%) are leading contributors to these impact categories. Based on the ecoinvent documentation (Nemecek and

Kägi 2007) these impacts may be driven by the upstream mineral extraction and resulting runoff impacts, however no additional information on impact sources of zinc, chromium, and copper was given.

P-fertilization contributed the greatest impacts in eutrophication and respiratory effects with 28% and 25% of the total impacts in those TRACI categories, respectively. Phosphate emissions to surface water (45%) and ground water (39%) and particulates emissions to air (52%) are leading contributors to these impact categories. No data existed for runoff or field emissions; so, it is important to note that all of these impacts result from manufacture and transport of fertilizers. There are estimates of run off and field emissions available in the ecoinvent database for more common European plants (i.e. cotton, rapeseed, wheat, & maize), which are calculated using emissions models SALCA-P (Prasuhn 2006) and SALCA-nitrate (Richner, Oberholzer et al. 2006), but none are available specifically for Guar.

Harvesting also contributes significant impacts across categories, showing the highest impact in the photochemical ozone formation category, contributing 41% of those total impacts. Methane emissions to air is the leading contributor to this impact category, accounting for 96% of the smog impacts. One method for improving the fidelity of this portion of the LCA model is to collect on farm harvest data, detailing specific equipment like the modification used in the combine harvester, in order to get more accurate impacts of harvest.

Interestingly, nitrogen fertilizer had one of the lowest impacts contributing to only about 11% of the total impacts in all the TRACI categories combined. This is a deviation from previous literature of guar agriculture results that show the nitrogen fertilization process as one of the higher impact processes (Gresta, De Luca et al. 2014). The system boundary of the model may have contributed to this difference since no field emissions were found in literature and thus could not be included in the analysis. In addition, specifics of the type and actual percentage of nitrogen being added during cultivation in literature were scarce as discussed in the methods. It is critical that future work understand the efficacies of N fertilizer usage and potential for field emissions.

Another limitation of the existing published data is that it is all from studies involving relatively small plots of land, ranging from 1-3hectares. This resulted in all the results being relevant for small plots but perhaps when scaling up to larger plots the results may not be consistent. One way to improve the results in future studies is to use field data from trial plots and commercial fields to have access to optimized results as well as much more likely commercial farm setting results.

3.3 Sensitivity analysis and scenario analysis

In the sensitivity analysis all of the inputs were varied to evaluate their effect on the overall TRACI impacts, as described in the methods. Irrigation was found to be the largest contributor to environmental impacts overall and it was also the input that the environmental and human health impacts were most sensitive to changing. Changes made to all the other model inputs altered the impacts much less or not at all. A few exceptions include P-fertilization which showed eutrophication, acidification, and respiratory effects to be most sensitive to its variation. N-fertilization, despite contributing so little to overall impacts, resulted in resource depletion to be as sensitive to its variation as irrigation.

Two scenario analyses were carried out; 1) irrigation: where minimum and maximum literature values were compared to the baseline average of literature values, and 2) nitrogen fertilizer: where alternative fertilizer types were evaluated. The irrigation scenario compared minimum and maximum irrigation literature values to the baseline. As expected, the results show that less water results in less impacts (Fig. 4). In this scenario, impacts were especially reduced in ecotoxicity, GWP, and resource depletion when the minimum irrigation value was used.

One thing to note is that this study only uses sprinkler irrigation in the analyses. This is a result of the available literature data only including sprinkler irrigation values. It is possible that other irrigation methods, like drip or flood, could have varying impacts. One comparison study by Eranki et al. for another desert crop, guayule, shows that drip irrigation was much more efficient in terms of water applied and yield then flood irrigation, and it also used less energy consumption and produced less environmental impacts (Eranki 2017). Perhaps similar field trial studies could provide data on which irrigation method is most efficient for guar cultivation. Field trial studies could also potentially provide enough data to support the development of a guar specific irrigation model instead of using the generic ecoinvent sprinkler irrigation impacts, which could provide guar specific impacts for each irrigation method investigated.

The nitrogen fertilizer scenario was conducted because of the great lack of detail provided in literature on N-fertilizer values. Many of the sources did not provide fertilizer types, brands, compositions, or N percentage. Urea was used as the baseline fertilizer in this study because it is incredibly common in agriculture. The scenario analysis compared urea to three other common fertilizers: monoammonium phosphate, calcium ammonium nitrate, and ammonium nitrate. The results in Fig. 5 show that across all the scenarios the life cycle impact categories that have the largest variation are acidification, ecotoxicity, eutrophication, and global warming impacts. When compared to the baseline N-fertilizer Urea, the only scenario that has a lower total impact is monoammonium phosphate. Using monoammonium phosphate decreases the impact in every impact category except acidification (increasing by < 1 %) and eutrophication (increasing by 5%). This decrease in total impacts can be contributed greatly to the composition of monoammonium phosphate. It contains both nitrogen and phosphorus and therefore using it for N fertilizer can also offset some of the need for adding P fertilizer. The other two scenarios (calcium ammonium nitrate & ammonium nitrate) increased the impacts in every impact category except for a 1% decrease in eutrophication when using ammonium nitrate. Ultimately this scenario analysis shows that using multinutrient fertilizers like monoammonium phosphate, that have both N and P within its composition may be the most efficient way to fertilize guar. Though these are promising preliminary results, it is important to measure field emissions and incorporate them into the analysis for future studies, which may significantly impact the overall results.

Conclusion

This study concluded that in terms of environmental sustainability, irrigation and harvesting methods offer the most opportunity for improved guar agricultural sustainability. This is promising because one of guar's prominent characteristics is its high water use efficiency and ability to grow in marginal soils. Lowering irrigation and water use can be implemented with simple management practice changes like optimizing irrigation. As we pursue adopting guar agriculture in the Southwest US, it will be critical to evaluate the type of irrigation to achieve maximum yields (e.g. drip, flood, sprinkler) and optimize fertilizer application rates with respect to yields. To truly understand the life-cycle environmental impacts of guar, LCA data bases must have measurements of field emissions including C soil fluxes, dust (i.e. PM) and field emissions of N and P from guar agriculture.

Declarations

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Conflicts of interest/Competing interests:

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Availability of data and material:

Data available upon request

Code availability:

Not applicable

Authors' contributions:

VeeAnder Mealing: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing - original draft; Writing - review & editing

Amy Landis: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing - review & editing

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Figures

Figure 1

Guar plant field in the US.

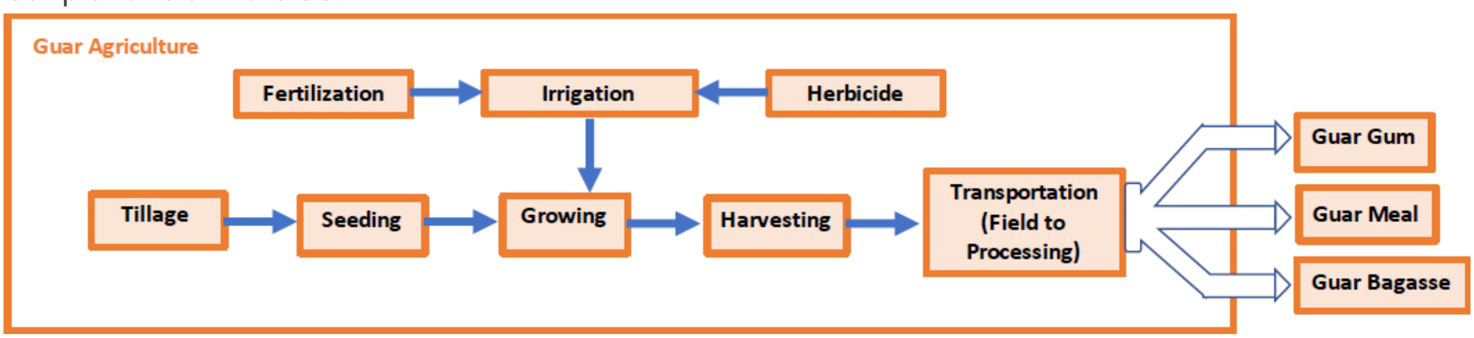

Figure 2

LCA system boundary for the agricultural processes involved in growing guar.

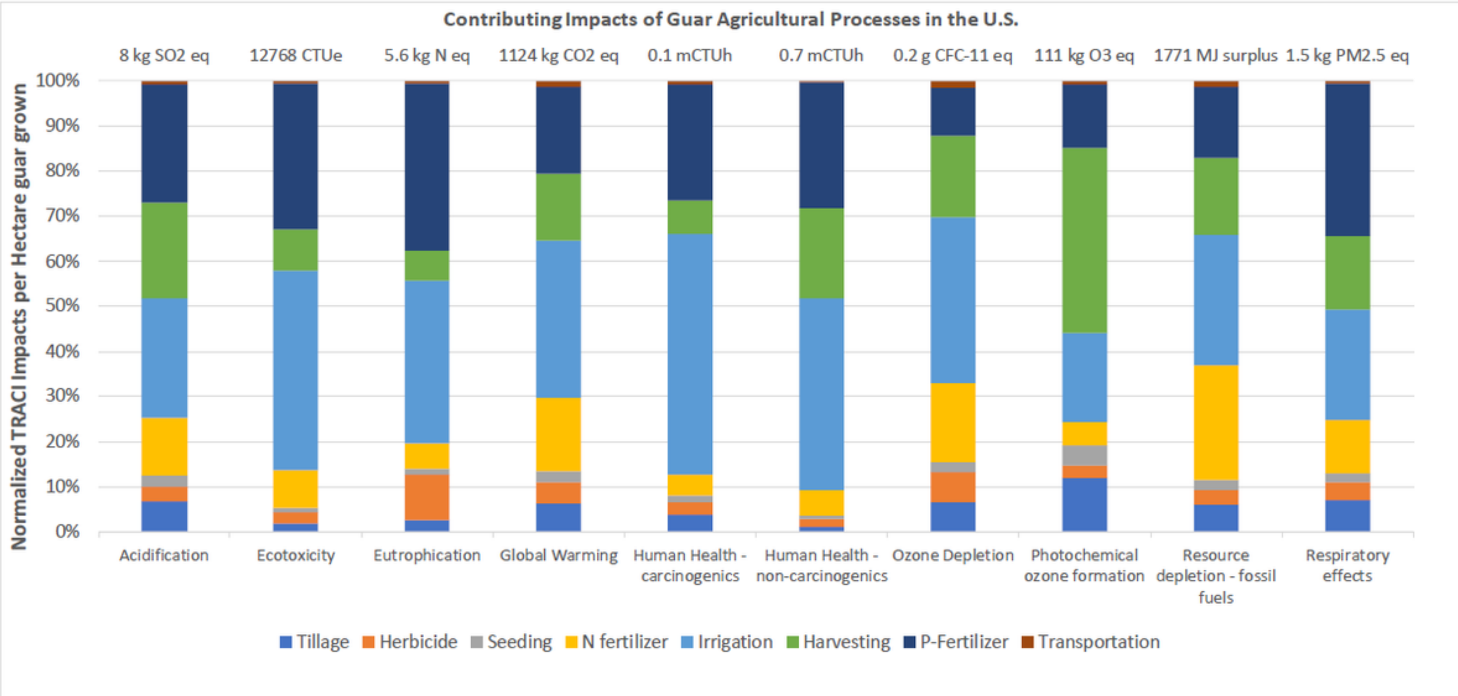

Figure 3

Life-cycle environmental impacts of guar agriculture The total impacts of each category are shown at the top of each bar with their associated units

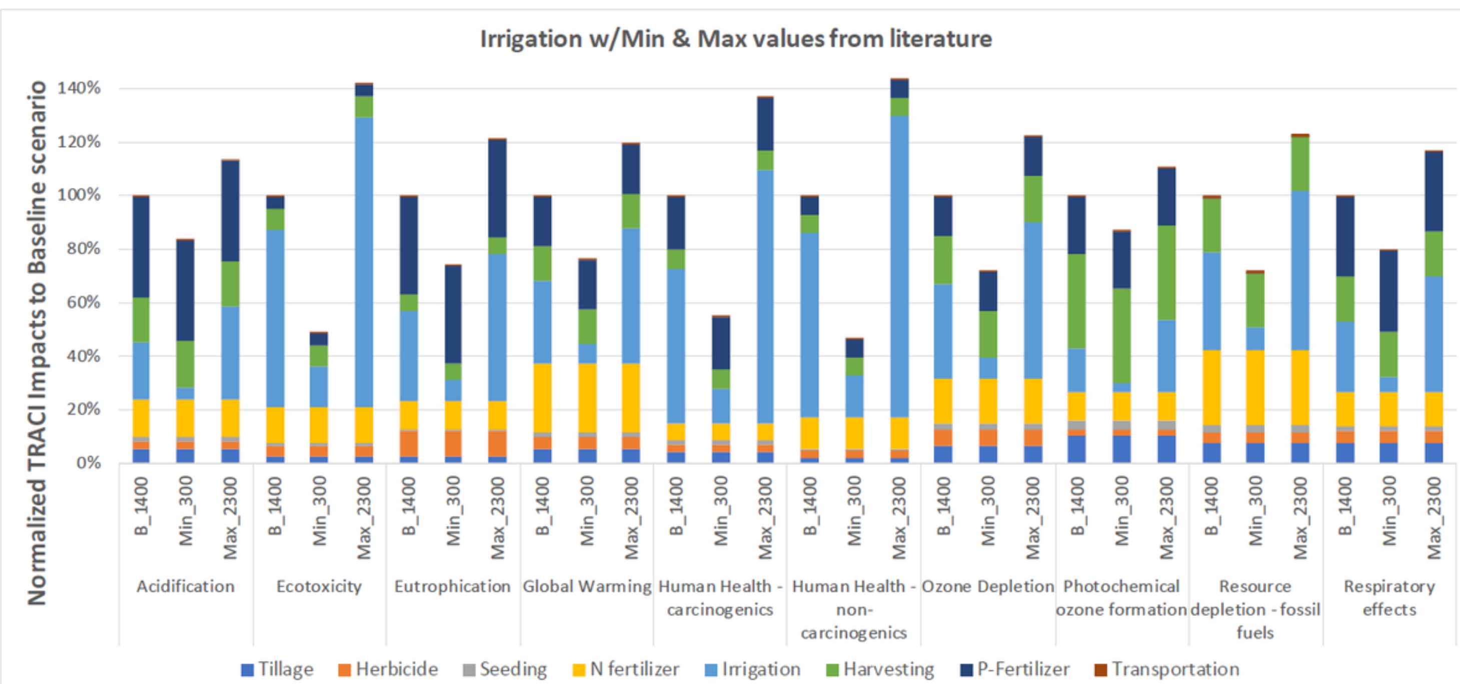

Figure 4

Comparison of contributing impacts of guar agriculture for irrigation scenario where baseline =1400m3/ha, Minimum =300m3/ha, and Maximum =2300m3/ha. Normalized to the total baseline impacts of each category.

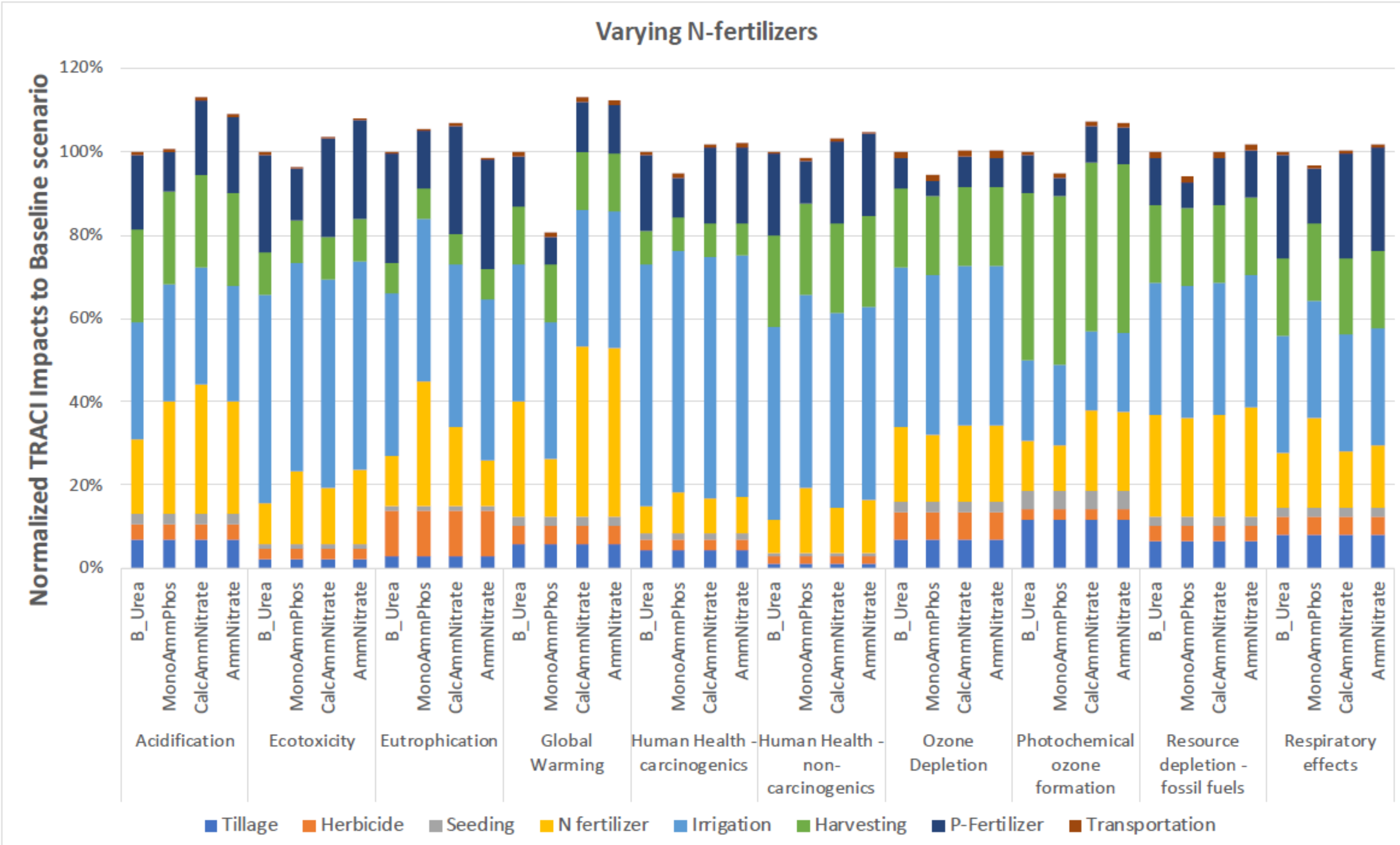

Figure 5

Comparison of contributing impacts of guar agriculture for nitrogen fertilizer scenario Comparing baseline N-fertilizer urea (B_Urea) to monoammonium phosphate (MonoAmmPhos), calcium ammonium nitrate (CalcAmmNitrate), and ammonium nitrate (AmmNitrate). Normalized to the total baseline impacts of each category.

Supplementary Files

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- Graphicalabstract062121.pdf
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