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Key Points:
- An adequate global diet can currently support an additional 0.8 billion people
- Seventy-six percent of countries are not self-sufficient regarding domestic calorie production
- Replacing the 2050 diet with a moderated one can feed 2–3 billion more people

Supporting Information:
- EFT2_49_BoxA1.tif
- EFT2_49_GlobCarryingCap_SuppInfo5.docx
- EFT2_49_readme.txt

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Moderating diets to feed the future

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Abstract Population growth, dietary changes, and increasing biofuel use are placing unprecedented pressure on the global food system. While this demand likely cannot be met by expanding agricultural lands, much of the world's cropland can attain higher crop yields. Therefore, it is important to examine whether increasing crop productivity to the maximum attainable yield (i.e., yield gap closure) alone can substantially improve food security at global and national scales. Here we show that closing yield gaps through conventional technological development (i.e., fertilizers and irrigation) can potentially meet future global demand if diets are moderated and crop-based biofuel production is limited. In particular, we find that increases in dietary demand will be largely to blame should crop production fall short of demand. In converting projected diets to a globally adequate diet (3000 kcal/cap/d; 20% animal kcal) under current agrofuel use, we find that 1.8–2.6 billion additional people can be fed in 2030 and 2.1–3.1 billion additional people in 2050, depending on the extent to which yields can improve in those periods. Therefore, the simple combination of yield gap closure and moderating diets offers promise for feeding the world's population but only if long-term sustainability is the focus.

1. Introduction

The world's population has rapidly increased over the past 200 years and is projected to continue doing so to century's end, when the global population is expected to reach a maximum [*United Nations—Department of Economic and Social Affairs*, 2013]. Predictions of the level and timing of this maximum are typically based either on historic demographic data [*Lee*, 2011] or on limiting global resources [*Cohen*, 1995]. The first approach leads to the question: "How much of Earth's resources will be needed to support these people?" The second asks: "How many people can these resources support?" When the population reaches the maximum size allowed by the available resources, one of two occurrences can be the result: either demographic growth ceases as the result of a Malthusian ceiling [*Malthus*, 1798, 1970; *Lee*, 2011], or innovation and adoption of new technology raises the ceiling of resource availability [*Boserup*, 1981; *Hermele*, 2014]. To prevent any sort of forcible natural constraint on population, humans have historically preferred the latter option [*Lee*, 2011]. Thus, it is likely that technology will keep intervening to increase the ceiling until population stabilizes as an effect of demographic and developmental drivers [*Godfray et al*., 2010]. With potential for agricultural expansion limited [*Cassman*, 1999; *Godfray et al*., 2010; *Foley et al*., 2011], increasing crop productivity toward the maximum attainable yield (i.e., yield gap closure) offers an important avenue by which technology can substantially improve global food supply [*Foley et al*., 2011; *Mueller et al*., 2012], though the literature has reached the consensus that increasing crop yields alone will be largely insufficient to meet future demand [*Godfray et al*., 2010; *Foley et al*., 2011; *Ray et al*., 2013]. This is because population growth, dietary changes, and biofuel use will play an important role in determining human demand and whether increases in crop supply can keep pace. Thus, a combination of four main solutions [*Godfray et al*., 2010; *Foley et al*., 2011] has been put forward: (1) agricultural intensification (i.e., increasing yields and harvests on current cropland), (2) increasing resource use efficiency and sustainability (e.g., fertilizers, irrigation water, and soils), (3) reducing food waste, and (4) moderating diets (especially the demand for meat and animal products).

Here we use an integrated calorie-based approach to examine the effect of diets (both current and projected) on the global carrying capacity, as constrained by domestic (country-level) crop production. By examining yield gap closures under different diet and biofuel use scenarios, we seek to accomplish two objectives. First, we seek to demonstrate to what extent fertilizers and irrigation can increase the ability of global crop production to support the world's population to mid-century. Second, we examine the effect of moderating diet on meeting current and future demands when combined with yield gap closure. Unlike previous analyses [*Kummu et al*., 2012; *Brauman et al*., 2013; *Cassidy et al*., 2013], we relate food to population size using country-specific dietary requirements [*FAOSTAT*, 2013], account for the caloric conversion from plant to animal calories [*Pimentel and Pimentel*, 2008], and, most importantly, consider the number of people who are able to be fed under current, future, and globally moderated, calorie-adequate (3000 kcal/cap/d; 20% animal) diets. As a country's diet can substantially differ from the global average or reference diet typically used in these previous studies, the novelty of our study lies also in considering several detailed diets and how many people can be supported under these scenarios, in comparing these estimates to population growth at both global and national scales, and in examining the self-sufficiency of each country's domestic food calorie production. Moreover, in order to consider the transformation from plant to animal calorie and its efficiency, we have introduced a proper conversion factor. Our approach also allows for comparisons between the food-supply benefits of a calorie-adequate global diet and the current and projected distributions of diets under different biofuel use scenarios and levels of yield gap closure. Thus, we ask to what extent different levels of yield gap closure of major food crops taken in combination with moderated diets (as well as reduced biofuel use) can potentially contribute to global food security by 2030 and by mid-century.

2. Methods

We considered agricultural production data for year 2000 and yields and yield gap closures for 16 major food crops (Supporting Information Table A2) [*Mueller et al*., 2012]. Country-specific information on average individual diet was obtained from the FAO Food Balance Sheets [*FAOSTAT*, 2013] for the year 2000. Data on total animal-source (i.e., meat, eggs, dairy, animal fat, and offals) production for each country were obtained from FAOSTAT [*FAOSTAT*, 2013]. Crop-specific values of energy to weight ratio from the Food Balance Sheets were used to convert the Mueller yield gap data and the FAO animal production data to total caloric production. Four diet scenarios were considered: (1) current (circa 2000) country-specific diet from FAOSTAT, (2) the FAO recommended calorie-adequate diet (i.e., 3000 kcal/cap/d; 20% animal calories), (3) projected diet for the year 2030, and (4) projected diet for the year 2050. These projected country-specific diets were calculated using regional values from *Alexandratos and Bruinsma* [2012], where the percent increases in total and animal calorie demand for 2000–2030 and for 2000–2050 were then applied to the current (circa 2000) country-specific demand of the countries contained within each region (Supporting Information Table A4). The number of people who could be fed under different diet and yield gap closure scenarios is calculated with the methodology presented in the Supporting Information (Supporting Information Tables A1–A5 and Supporting Information Box A1).

3. Results

Our estimate for the number of people able to be supported by global production of major crops in the year 2000 is 5.83 billion people (when accounting for waste and biofuel use). This is consistent (4.9% difference) with the UN estimate of 6.13 billion [*United Nations—Department of Economic and Social Affairs*, 2013]. Under the current scenario (diet, waste, and biofuel use in 2000), we calculate that complete yield gap closure would support 3.94 billion additional people. This represents a gain in vegetal production of major food crop calories of 3.50×10^{15} kcal (compare to 5×10^{15} kcal for 95% closure without waste or biofuel use calculated previously [*Foley et al*., 2011]). Under the status quo, this level of production would be more than capable of feeding the world in 2030 (8.42 billion people) and at mid-century (9.55 billion people). However, this does not consider future changes in diet and biofuel use (Figure 1), nor the rate at which yield gap closure can occur [*Ray et al*., 2013]. If biofuel production were to increase in a "business-as-usual" scenario [*OECD-FAO*, 2011] with the projected diet of 2030, the population able to have their dietary needs met under complete yield gap closure would be substantially reduced to 7.19 billion people, a deficit of 1.23 billion people globally. Conversely, if a calorie-adequate global diet is consumed in 2030, yield gap closure would support 9.32 billion people, even if biofuel production continues to increase as it has.

While the global average daily diet was 2700 kcal per person in 2000, diets varied widely by country, from Eritrea (1506 kcal/cap/d, 8% animal) to Austria (3809 kcal/cap/d, 33% animal). When we consider a transition from current diet to a calorie-adequate diet with current biofuel use and waste, 820 million additional

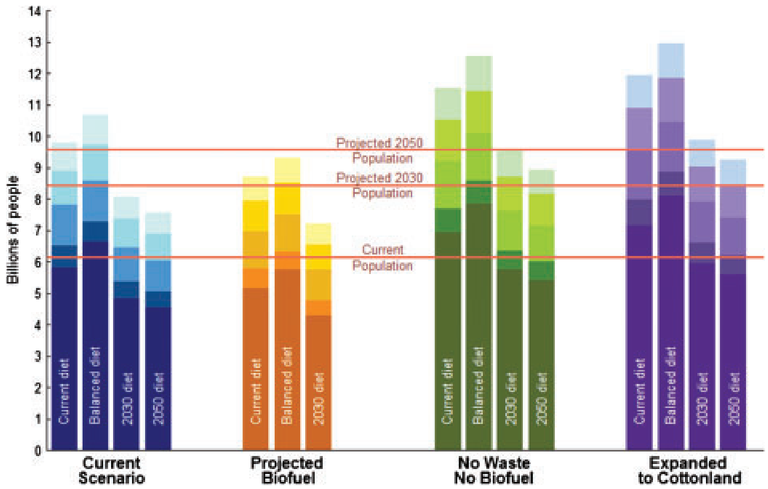

Figure 1. Yield gap closure for different scenarios of dietary change, biofuel use, and waste. The five segments of each column represent the population potentially supported by domestic production under year 2000 yields and yield gap closures of 50%, 75%, 90%, and 100%. For expansion onto land originally used for cotton, the fraction of total land used by each major crop was calculated for each country, and the area of cotton land was divided accordingly.

people can be fed, showing that modifying diets (in terms of calories) to be more globally uniform can substantially improve the number of people fed [*Godfray et al*., 2010; *Foley et al*., 2011] and that caution must be used when drawing conclusions based on average global diets. Our findings also add to a recent study (~110 million additional people assuming a 3000 kcal diet) based on improved agricultural use of water resources [*Brauman et al*., 2013] and indicate that other yield-increasing inputs (e.g., fertilizer and pesticide use) may need to feature more prominently in closing yield gaps, as has been the case throughout the twentieth century [*Erisman et al*., 2008].

We estimate that 56% of the total production of (non-seafood) animal products originated from rangeland in 2000, representing a significant contribution to diets globally [*Godfray et al*., 2010]. Also, our global estimate (derived from the FAO Food Balance Sheets) of wasted food (~14%) agrees well with the 16% previously found for lost or wasted food within the food supply chain [*Kummu et al*., 2012].

Lastly, by comparing the number of people potentially supported by domestically produced calories with the current (year 2000) population of each country, we determined the countries which are currently most dependent on imported calories (Figure 2). We found that 917 million people (~15% of global population) needed foreign-produced calories in 2000 (Figure 2), a value that agrees well with *Fader et al*. [2013]. Moreover, the countries with larger populations also tended to be more self-sufficient in terms of domestic crop production. Furthermore, when diets are adequate globally, a greater number of countries can achieve self-sufficiency in terms of calorie production. Specifically, the percent of countries in obvious calorie deficit (and which are therefore reliant on food trade) modestly decreases from 77% under the current diet to 70% under a calorie-adequate global diet.

4. Discussion

Now more than ever, the relationship of humankind to the planet's natural constraints is dependent on human choices relating to diet, energy, and demographic changes [*Cohen*, 1995]. Technology has continually played a role in increasing the planet's carrying capacity, allowing the combination of agricultural expansion and elevated yields to meet increasing human demand [*Boserup*, 1981; *Hermele*, 2014]. However, decisions on how to feed a global population have become more difficult as the environmental impacts from increased agricultural production continue to mount. Further agricultural expansion exemplifies this dilemma and may provide immediate benefits to food availability compromising the ability of ecological systems to maintain biodiversity and carbon storage [*Foley et al*., 2011]. Moreover, many agree that present global consumption far exceeds long-term sustainable levels [*Rockström et al*., 2009; *Brown*, 2011; *Gaodi et al*., 2012].

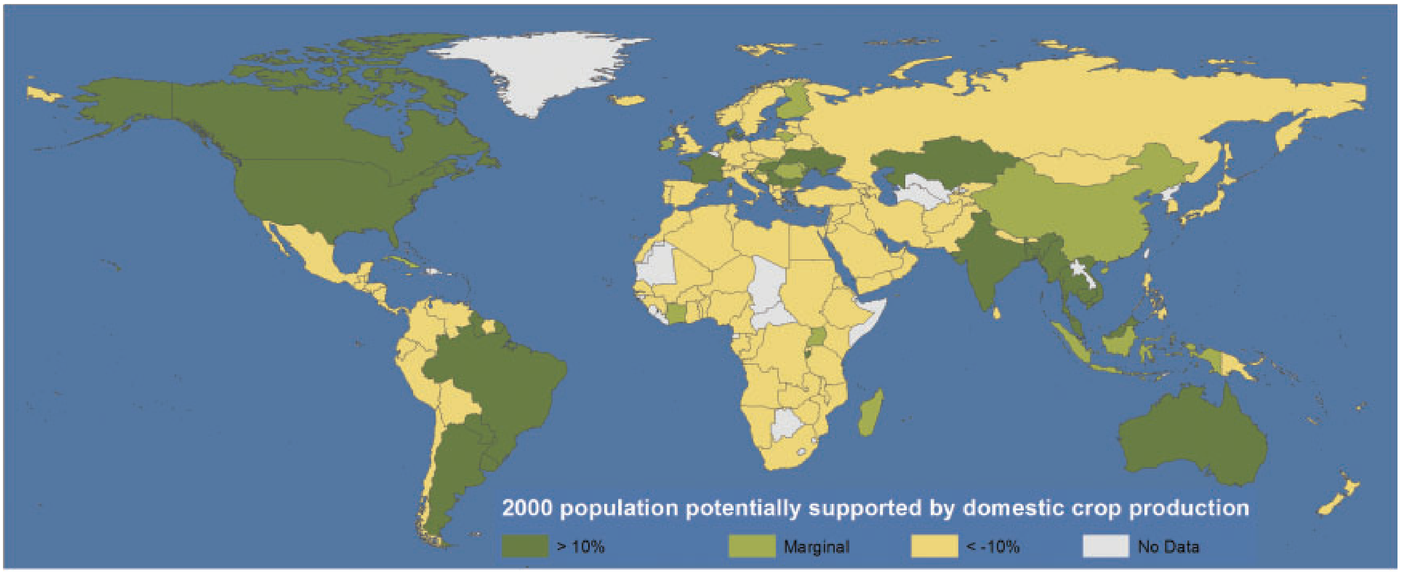

Figure 2. Countries in conditions of food calorie self-sufficiency, deficit, and marginal self-sufficiency or dependency, based on current diet, waste, and biofuel use and the year 2000 yields. Out of 154 countries, 117 countries are in obvious calorie deficit. For self-sufficient countries, the domestic caloric production from crops is at least 10% greater than what is required by the domestic population. For deficit countries, the domestic caloric production from crops is at least 10% less than what is required by the country's population.

These findings make apparent the current dependence of many countries on global food trade and the potential for this dependence to increase [*Fader et al*., 2013]. As seen with the trade of virtual water, a greater dependence on trade will likely decrease societal resilience [*D'Odorico et al*., 2010]. Further, in response to recent spikes in food prices resulting from droughts or other climate extremes in years of increasing demand for agricultural products, the governments of exporting countries have banned or limited their exports to ensure their own food security [*Fader et al*., 2013]. Thus, the food security of import-dependent countries (much of the world is reliant on food trade to meet domestic needs) is strongly affected by the uncertainty and unreliability of the food trade market. With this in mind, our study's comparison between domestic calorie production and demand thus asks what would happen if trade did not occur. This in turn sheds light on self-sufficiency (both present and future) of domestic calorie production under a number of scenarios in terms of domestic crop production and shows that in some cases improved yield can potentially increase food security (particularly in places of slow population growth). In all of this, our study evaluates countries' self-sufficiency considering the very extreme case that international food trade would cease completely, which is clearly unlikely. Overall, our findings reinforce that simply closing yield gaps is not sufficient to meet future dietary needs under a variety of scenarios, regardless of the rate of yield gap closure [*Ray et al*., 2013]. While closing yield gaps alone is largely insufficient, we do see that, when yield gap closure is combined with a calorie-adequate global diet, these two approaches alone can largely meet global demands to mid-century (Figure 1) and that minimizing the use of crop-based biofuels further improves the outlook. In some cases moderating diets can also serve to meet a nation's calorie demand domestically. To achieve this greater self-sufficiency however would entail a reduction in per capita demand and would likely prove difficult given the economic, social, and cultural implications of diet. Overall, it is apparent that, while moderating diets can reduce global demand, food trade will still need to feature prominently under such scenarios to ensure food access and security. In contrast to the global calorie-adequate diet, we find that projected changes in diet as a result of increasing global development and affluence will likely result in greater food insecurity globally, as even the highest attainable yields cannot meet the appetite of a rapidly growing population over the next several decades. In addition, the fact that greater affluence leads to richer diets is compounded by recent trends in the livestock sector toward intensification (i.e., grain-fed, high-density animal production) [*Delgado et al*., 1999; *Steinfeld et al*., 2006]. From a resource perspective, it is encouraging that much of this intensification (and the increase in animal production overall) is attributable to more resource-efficient animals (e.g., chickens and pigs). Yet while a greater reliance on these non-ruminant species with small area requirements may alleviate stress on grazing systems, this can also mean increased competition between food-crop and feed-crop production for land and water resources [*Naylor et al*. 2005] and further separation of consumers from the environmental impacts of their food production [e.g., *Galloway et al*., 2007]. If supply, in fact, becomes constraining as a result of livestock production and other unprecedented demands, this may mean that future dietary demand as well as dependence on crop-based biofuels will need to decline. Otherwise, these potentially unsustainable demands may profoundly impact food availability for human consumption in the near future. As a brief aside, we should also note that, while not examined in depth here, other important ways to potentially improve global food supply are through (1) increasing the frequency of crop harvesting, where it has been shown that many regions have large "harvest gaps" [*Ray and Foley*, 2013] and (2) reducing food waste, where it has been shown that halving the amount of waste in the food supply chain could be 1 billion additional people [*Kummu et al*., 2012].

In this study, yield gap closure is achieved by increasing nutrient and water availability through investments in fertilizers and irrigation technology, a process often delayed by social, cultural, technical, and financial obstacles. Moreover, crop yields remain susceptible to stagnation of actual [*Ray et al*., 2012] and potential yields (i.e., yield ceiling) [*Lobell et al*., 2009] and the effects of climate variability and change [*Lobell et al*., 2011]. Changes in growing season length and drought occurrences thus constitute serious threats to the predictability and reliability of global agricultural production [*Lobell et al*., 2011; *Wheeler and von Braun*, 2013]. On the other hand, with recent increases in large-scale land acquisitions in the developing world (and the rapid improvement in agricultural technology that they can bring), there may be a global potential for major crop yields to improve more rapidly than historically observed [*Rulli and D'Odorico*, 2014]. This may mean that crop production is better able to attain the doubling in supply that has been predicted to meet mid-century demand [*Tilman et al*., 2011; *Ray et al*., 2013]. In highlighting these various additional influences on future crop yields, we should clearly state that the effects on global food security of climate change, carbon dioxide fertilization [*Schmidhuber and Tubiello*, 2007], genetically modified organisms (GMOs), and access to crop production [*Brown et al*., 2013] were not considered in this study. In addition, feedbacks resulting from potential social (e.g., modified diet in response to availability), economic (e.g., increased food prices), and policy (e.g., biofuel additive cap [*European Parliament*, 2013]) responses to a strained food supply were not considered.

Use of food crops as biofuels is another significant factor influencing future food security and demonstrates that the outlook for meeting human demands largely depends on the decisions made now regarding biofuel policy and the pace of and extent to which these new policies are implemented [*Hill et al*., 2006; *Hermele*, 2014]. Providing possible insight into how major biofuel producers (and societies in general) may be expected to prioritize agricultural resources in the coming decades, recent European legislation placed a cap on the amount of food-based biofuel added to transportation fuel [*European Parliament*, 2013]. Thus, due to the relatively rapid changes in policy that can occur regarding the use and production of crop-based biofuels, we do not consider biofuel scenarios for 2050.

Though changes in biofuel policy can improve the outlook for meeting future human demand, in this paper we have set out to examine the consequences of dietary change in particular. Future diets will be characterized by transitions to greater percentages of meat, reflecting economic and developmental improvements [*Tilman et al*., 2011]. As diet has social, cultural, and economic implications, encouraging smaller proportions of meat may be one of the more difficult avenues to pursue in seeking to decrease demand [*Godfray et al*., 2010], but can also offer some of the largest benefits in increasing the number of people able to be fed [*Cassidy et al*., 2013; *Hermele*, 2014]. This is particularly true if diets transition toward less demand for animal-source products, as the calories from these products require substantially more resources to produce. Alternatively, it may be possible to rely less on grain-fed animal production, increase the animal production of rangelands, and enhance the reliance on fisheries (particularly aquaculture) to ensure resource savings [*Gephart et al*., 2013]. In this way, a greater amount of cereals will be available for direct human consumption [*Cassidy et al*., 2013]. Though this offers promise for global food security, it also appears that progression toward an adequate diet for countries below this recommended level [*International Food Policy Research Institute (IFPRI)*, 2012] conflicts with the need to rapidly feed greater numbers of people in the coming decades.

The United States and Brazil, two of the world's major biofuel producers, serve as cautionary examples of how current calorie surplus can be quickly exhausted in the future as a result of energy choices, dietary behavior, and demographic change. Largely used to meet the country's high demand for animal-based calories, maize in the United States made up 86% of the country's plant-based feed (by weight) in 2000 and is increasingly diverted for biofuel production. Thus, as a greater percentage of maize production is used for energy, the remaining percentages for animal production and food for direct human consumption are reduced, and could result in less willingness to export to countries dependent on this production. A reduced ability to export major crops may also occur in Brazil where conflicts over land may intensify in coming decades [*Hermele*, 2014]. Here, increases in yield alone would be insufficient to prevent Brazil's transition to calorie deficit, if biofuel production and dietary demand continue to increase. Unlike the United States, where the frequency of crop harvesting is close to the maximum, Brazil has the potential to more than double the frequency with which it harvests crops [*Ray and Foley*, 2013] and can in this way greatly increase domestic calorie delivery. Under this scenario, Indonesia and Papua New Guinea undergo a similar fate due to expanding oil palm production, but again also have a large potential for increasing crop harvest frequency.

China and India offer a different perspective, in that they are not major biofuel producers, but population growth (particularly in India) and increased consumption of animal-based calories (particularly in China) may serve to take these countries below the threshold of self-sufficiency for domestic calorie production, even if yield improvements are realized. China has limited options, especially, in terms of agricultural intensification, as the country's potential for increasing harvest frequency is also low [*Ray and Foley*, 2013]. As further evidence of China moving toward maximizing its domestic resources, in 2010, it had already become a net importer of virtual water [*Carr et al.*, 2013] and food (in tons [*FAOSTAT*, 2013]). The transition of India, however, can be expected to occur later (if at all) as it reaches its peak population some 30 years after China [*United Nations — Department of Economic and Social Affairs*, 2013] and has more time to be proactive. More broadly, rapid population growth in Asia and Africa may exacerbate issues of food security and malnourishment [*IFPRI*, 2012], as improvements in crop production may not keep pace with growing demand. In addition, the impacts of climate change on domestic crop production in these most vulnerable countries are expected to become more severe with time [*Schmidhuber and Tubiello*, 2007; *Wheeler and von Braun*, 2013]. However, in these regions, the large potential to increase yields and harvesting frequency (outside of China and India) offers hope in the ability to increase food supply [*Ray and Foley*, 2013]. In all of this, the long-term sustainability of such agricultural practices will become a more pressing issue in the coming decades.

5. Conclusion

Closing yield gaps offers great benefits for additional global food supply, especially in areas of high food insecurity [*IFPRI*, 2012], but will likely not meet increased future global demand on its own. This is particularly true given recently observed crop yield stagnations and the potential for this to occur in more places in the future [*Lobell et al.*, 2009; *Ray et al.*, 2012]. As in the past, new technologies and innovation will likely act to increase global food supply, but the multiple demands on the global food system dictate that yield gap closure can only *ever* be part of the solution toward meeting future needs. While population growth, dietary changes, and biofuel production can act synergistically to the detriment of many countries' prospects for food security, the combination of moderated diets and improved crop yields offers great promise but can also be one of the more difficult avenues to pursue. Our approach considering country-specific dietary requirements highlights the fact that a greater focus on making dietary demand more equitable can be one of the most beneficial solutions for the prospects of global food security but can make some of the poorest countries less able to feed their populations.

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