Decreases in global beer supply due to extreme drought and heat

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Figs. 1-5

Supplementary Online Materials:

Materials and Methods
Supplementary References
Supplementary Figures [1-40]

Beer is the most popular alcoholic beverage in the world by volume consumed, and yields of its main ingredient, barley, decline sharply in periods of extreme drought and heat. Yet, although the frequency and severity of drought and heat extremes increase substantially in range of future climate scenarios by 5 Earth System models, the vulnerability of beer supply to such extremes has never been assessed. Here, we couple a process-based crop model (DSSAT) and a global economic model (GTAP) to evaluate the effects of concurrent drought and heat extremes projected under a range of future climate scenarios. We find that these extreme events may cause substantial decreases in barley yields worldwide. Average yield losses range from 3% to 17% depending on the severity of the conditions. In turn, decreases in the global supply of barley lead to proportionally larger decreases in barley used to make beer, and ultimately result in dramatic regional decreases in beer consumption (e.g., -32%) and increases in beer prices (e.g., +193%). Although certainly not the most concerning impact of future climate change, climate-related weather extremes may threaten the availability and economic accessibility of beer, thereby adding insult to injury. ***[193 words]***

Rising incomes are strongly correlated with increases in consumption of resource-intensive animal products (meat and dairy)[1,2], processed foods[3], and alcoholic beverages[4] (Figs. SI-1 and SI-2). Despite concerns that such trends are not healthy or environmentally sustainable[2,5,6], global demand for these foods and beverages will continue to grow as economic development proceeds[7].

At the same time as demand for such products is increasing, climate change threatens to disrupt the supply of agricultural products[8-12]. A substantial and increasingly sophisticated body of research has begun to project the impacts of climate change on world food production, focusing on staple crops of wheat[13,14], maize[15,16], soybean[17,18], and rice[19,20]. However, if adaptation efforts prioritize necessities, climate change may undermine the availability, stability and access to “luxury” goods to a greater extent than for staple foods. Although some attention has been paid to the potential impacts of climate change on luxury crops such as wine and coffee[21-23], the impacts of climate change on the most popular alcoholic beverage in the world, beer, have not been carefully evaluated.

Here, we assess the vulnerability of the global beer supply to disruptions by extreme drought and heat events that may occur during the 21st-century as the climate changes; these are the main mechanisms by which climate damages crop production[24,25]. Details of our analytical approach are in Methods and in Section 2 of SI. In summary, we develop an extreme event severity index for barley based on extremes in historical data (1981–2010) and use it to characterize the frequency and severity of concurrent drought and heatwaves (i.e. extreme event severity) under climate change as projected by five different Earth System Models (ESMs) during 2010-2099. Extreme event years are years with concurrent drought and heat (i) during barley growing season and (ii) in areas where barley is now grown which are (iii) more severe than 100-year events in the historical record (as a weighted average of the barley-growing grid cells). Among the 450 modeled years (90 years * 5 ESMs) of each Representative Concentration Pathway (RCP), we identify 17, 77, 80, and

139 such extreme event years in RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. We then model the impacts of these extreme events on barley yields (the primary agricultural input to most beer[26]) in 34 world regions (most of which are individual countries) using a process-based crop model (DSSAT). Next, we examine the effects of the resulting barley supply shocks on the supply and price of beer in each region using a global economic model (GTAP, a computable general equilibrium model). Finally, we test the sensitivity of our results to key sources of uncertainty including extreme events of different severities, technology and parameter settings in the economic model[27,28]. Thus, we assess future sudden changes in barley production and subsequent changes in beer consumption across the world in years when extreme drought and heat occur. Furthermore, because such extreme events could occur in any future year and it is not possible to anticipate how agricultural and socio-economic systems will evolve, we analyze impacts based on the recent geographical distribution of barley crops, recent levels of economic development and structure, recent population, and recent demands for barley and beer (i.e. as of 2011, which is the latest available year for data of our economic model).

Extreme events limit beer supply

Fig. 1a shows the relationship between future increases in global mean (land) surface temperatures and the index of extreme event severity (i.e. the prevalence and magnitude of concurrent extreme drought and heat during barley growing season and over barley-growing regions) for each “extreme event year” we identify (Fig. SI-13 shows historical trend). The trend is relatively flat as global mean (land) surface temperatures increase up to ~2°C, above which there is a rapid increase in extreme event severity up to ~7°C of warming (RCP8.5, Fig. 1a). The corresponding annual likelihoods of concurrent drought and heatwave in the pathways and models are summarized by the bars in Fig. 1b. On average, the annual likelihood of such extreme events projected by the climate models over the 21st century is ~4% in RCP2.6 (i.e. an emissions pathway likely to avoid 2°C of mean temperature increase during this century), increasing to ~17-18% in RCP4.5 and RCP6.0 (temperature increases of 3-4°C), and up to ~31% in RCP8.5 (temperature increases >4°C). Importantly, the likelihoods of extreme events in the second half of the century (top of error bars in Fig. 1b) are considerably greater, with extreme events occurring roughly 1 in every 3 years in RCP6.0 (top whisker of orange bar in Fig. 1b) and roughly 1 in every 2 years in RCP8.5 (top whisker of red bar in Fig. 1b) (Figs. SI-14 and SI-15 show spatial pattern).

Crop modeling using the weather conditions from each extreme event year projects the average barley yield losses shown in Fig. 2 (see Fig. SI-21 for uncertainty of yield losses). The greatest losses occur in tropical areas such as central and south America and central Africa (Fig. 2). In the same years, yields in temperate barley-growing areas such as the Europe decrease rather moderately (yellow in Fig. 2) or even increase somewhat (blue and dark blue in Fig. 2) including northern parts of the U.S. and northwest Asia.

The box-and-whisker plots at the right in Fig. 2 show the global distribution of barley yield changes. Global mean barley yields decrease during extreme event years, with more severe extreme events and yield losses associated with higher emission pathways; average yield reductions during these years are -3%, -9%, -10%, and -17% in RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. Yield impacts are thus well-matched with increases in extreme event severity (See correlation of yield loss and severity index in Fig. SI-20).

Although we assume that the current geographical distribution and area of barley cultivation is maintained, final barley production may not decrease to the same degree as estimated by the weather-driven crop model if agronomic inputs are diverted to barley production during extreme events—labor, machinery, fertilizer, irrigation, etc. (same as Nelson 2014[28]; Iglesias 2012[29]). The contribution of these inputs is modeled in the GTAP model as the nonlinear reduction of labor and other inputs. For example, under RCP8.5, increases in labor and capital factors of production mean that an 17% mean decrease of DSSAT-modeled barley yields worldwide (Fig. 2a) corresponds to only a 15% reduction in the global barley production (Fig. 3, “global” panel; also see Figs. SI-21 and SI-22 for national/regional barley yield/production changes).

Our economic modeling shows that global- and country-level barley supply declines progressively in more severe extreme event years (i.e., under higher emissions pathways; solid bars in Fig. 3), with largest mean supply decreasing by 27-38% under RCP8.5 in some European countries (Belgium, Czech Republic and Germany). Barley supply changes are not only affected by shifts in barley production, but also by international trade among countries. For example, in some countries whose domestic production decreases (e.g., Brazil, relative area of black hatching), trade between countries mediates the effects of changes in local production on country-specific barley supply, with an increasing share of imported barley being consumed. On the other hand, depending on the magnitude of production losses, barley-exporting countries may conserve their domestic production via reduced net export (e.g., Australia; decreasing length of red hatches in Fig. 3), or increase their exports to meet demand in other countries (e.g., the U.S.); however, the larger decreases in barley supply occur in countries which rely heavily on barley imports (e.g., China, Japan, and Belgium), as demand for such imports exceeds any increases in exports.

Changes in barley supply due to extreme events will affect the barley available for making beer somewhat differently in each region as the allocation of barley among livestock feed, beer brewing, and other uses will depend on region-specific prices and demand elasticities as different industries seek to maximize profits (Fig. 3, yellow bars indicate barley allocated to the beer sector). In recent years, the beer sector consumes around 17% of global barley production, but as seen in Fig. 3, this share varies drastically across major beer-producing countries, for example from 83% in Brazil to 9% in Australia. Further analyzing the relative changes in shares of barley use, we find that in most cases barley-to-beer shares shrink more than do barley-to-livestock shares, showing that food commodities (in this case, animals fed on barley) will be prioritized over luxuries such as beer during extreme event years. At the global level, the most severe climate events (i.e. RCP8.5) cause the barley supply to decrease by 15% (ranging from 6-22% in our uncertainty analysis over 25-75 percentiles), but the share of barley-to-beer decreases by 20% (from the initial 17% of all barley down to 14%). Among countries, we see that the reduction in barley consumption in RCP8.5 is greatest in

Belgium (38% with uncertainty range of 18-57%), where the barley to beer share decreases by 48% (from the initial 28% to 14%). Therefore, future drought and heat events will not only lower the total availability of barley for most key countries but will also reduce the share of barley used for beer production (also see Figs. SI-24 and SI-25 for changes in absolute and relative shares in all countries/regions).

Global reductions in beer consumption

Ultimately, our modeling suggests that increasingly widespread and severe droughts and heat under climate change will cause considerable disruption in global beer consumption and increase beer prices (Figs. SI-26 and SI-27). During the most severe climate events (e.g., RCP8.5), our results indicate that global beer consumption would decline by 16% (0-41%) (roughly equal to the U.S.'s total annual beer consumption in recent years), and that beer prices would on average double (100-656% of recent prices). Even in less severe extreme events (e.g., those occurring in RCP2.6 simulations), global beer consumption drops by 4% (0-15%) and prices jump by 15%(0-52%).

Fig. 4 shows, for each RCP, ten key countries according to changes in total beer consumption by volume (left column; Figs. 4a-4d), changes in the price of beer (middle column; Figs. 4e-4h), and changes in the per capita consumption of beer (right column; Figs. 4i-4l) (see percent changes for all main beer consuming countries in Figs. SI-26 to SI-28; absolute changes in Figs. SI-30 to SI-32). For comparison, consumption data from ten key countries in recent years is shown in Fig. 5 (see Figs. SI-3 to SI-5 for additional details). Total beer consumption decreases most under climate change in the countries that consume the most beer by volume in recent years (Fig. 4a). For example, the volume of beer consumed in China—today the largest consuming country by volume (Fig. 5a)—decreases by more than any other country as the severity of extreme events increase (we model a decrease in consumption in China of 8.9% under RCP8.5, equivalent to 4.34 billion liters, Figs. 4b-d). Meanwhile, some countries with smaller total beer consumption face prodigious reductions in their beer consumption: the volume of beer consumed in Argentina falls by 0.27 billion liter (0.03-0.44 billion liter), equivalent to a 32% (0-56%) reduction, during more severe climate events (i.e. RCP8.5; Fig. 4d); even in the least severe climate events (i.e. in RCP2.6; Fig. 4b), total beer consumption in Argentina and Canada decreases by 16% (2-27%) and 11% (2-17%) respectively.

Countries where beer is currently most expensive (e.g., Australia and Japan) are not necessarily where future price shocks will be the greatest (Figs. 4e-4h and Fig 5b). Changes in the price of beer in a country relates to consumers' ability and willingness to pay more for beer rather than consume less, such that the largest price increases are concentrated in relatively affluent and historically beer-loving countries. For reference, the \$4.84 (\$1.07-8.49) increase in the price of a five-hundred-mL bottle projected for Ireland under RCP8.5 is equivalent to a price hike of \$20.61 (\$4.55-36.15) per 6-pack of 12-ounce beers i.e., about 193% (43-338%) increase to pre-event price (12 US fl oz ≈ 355 mL) (Fig. 4h).

At the level of individuals in each country, the greatest reductions tend to better align with those countries that consume the most beer per capita in recent years (Figs. 4i-4l). For example, the highest levels of annual per capita consumption, in Ireland and Czech Republic, are today 276 and 274 five-hundred-mL bottles, respectively (equivalent to ~5 bottles per week or a bit more than a 6-pack per week). The projected impacts of climate change would cause a decrease in Ireland and Czech Republic of 81(47-125) and 81 (55-117) bottles per year under RCP8.5 (Figs. 4l). Proportional but somewhat smaller absolute decreases occur in other countries, including Germany, Austria, and Belgium.

Impacts of changes in mean climate

We also assessed the impacts of changes in mean climate on barley yield and beer supply globally and at the level of specific countries (Figs. SI-33 to SI-37). Under RCP2.6, gradual changes in temperature and precipitation reduce global barley yields slightly (Fig. SI-34). In higher warming pathways, changes in mean temperatures and precipitation substantially decrease barley yields, though not as much as during years with extreme drought and heat (Fig. SI-33). Over the long term, adaptation efforts may be able to offset mean damages to barley production from climate change through changes in agronomic practices, cultivars, or barley growing areas, however extreme events are difficult to manage under any climate regime. Although the magnitude of potential climate adaptations in the agricultural sector remains a topic of much debate[30], it is clear that extreme climatic events will pose serious supply disruptions. For example, assuming that adaptation efforts are perfectly successful in preventing yield decreases due to changes in mean climate, extreme events will still result in increasingly large production losses, and the frequency and severity of these events increases with temperature increase (Fig. 1 and Fig. SI-33). Thus, our focus here is on the impact of extreme events that could occur in any year.

Uncertainties and limitations

We perform a sensitivity analysis to test the relative importance of different input parameters (SI section 3.5). We vary each input by +/- 10% in turn, observing the effect on global beer consumption. The results are shown in Figs. SI-38 and SI-39. The efficiency with which barley is converted to beer (the ‘technology’ bar) has the largest effect across all the emissions pathways, followed by physical shocks of, e.g., drought/heat severity and stockpiling, with elasticities and other economic parameters.

In addition, our methodological approach in this study has some important limitations deserving discussion, including our use of a single crop model to estimate barley yields, and the fact that our estimates of impact are based on the current agricultural practices, global economy, population, and prevailing dietary/beverage preferences.

A single crop model (DSSAT) is used to evaluate the effects of drought and heat on barley yields. The DSSAT model is known to underestimate yield damage caused by spikelet sterility and leaf senescence under droughts and heatwaves[31,32], and neglects the possibility that pest and disease attacks could also happen concurrently[33]. However, numerous studies demonstrate model skill in reproducing historical barley yields[34-38], and a Europe-focused model intercomparison shows that yields projected by the DSSAT model are near the mean of nine crop models[39].

Our results reflect impacts of extreme events as though they happened in today's world. For example, we do not assess the effect of future changes in barley agriculture, such as increases in farm productivity due to new technology; the use of different, more drought- or heat-tolerant barley cultivars; or increases in barley stockpiling (we review challenges of stockpiling barley for beer in SI section 2.4). Similarly, global population and socio-economic conditions are held constant. Further studies may incorporate these factors for a more complete picture of beer supply in the future; as a first step, we seek to isolate the effects of extreme climatic events holding all other conditions constant.

Limiting assumptions about socio-economic change is also a common approach to isolate the influence of climate change[40,41], although changes to actual future beer consumption will also be influenced by changes in economic structure, trade, income, demographic, and lifestyle changes[42] in each region. The Shared Socio-economic Pathways (SSPs)[43,44] project continued population and economic growth: e.g., in the "middle-of-the-road" SSP2, global population increases by 35% in 2050 relative to 2010 and global GDP triples over the same period. In the countries with the greatest total beer consumption in recent years, such as China, Brazil and Russia, SSP2 projects GDP to increase by a factor of 3-6. Under such growth, per capita beer demand is also likely to increase. Similarly, population in the countries whose per capita beer consumption is highest in recent years, such as Ireland, Belgium and Czech Republic, increases by 10%-40% in SSP2, which will probably also lead to an increase in the total beer demand. Although we do not explicitly model these trends, they are likely to exacerbate the beer shortages and related price increases that we model during barley crop failures.

Conclusions

In conclusion, concurrent extremes of drought and heat can be anticipated to cause both substantial decreases in beer consumption and increases in beer price, and the frequency and severity of these extreme events is correlated with future increases in mean surface temperature increases under climate change. Although the effects on beer may seem modest in comparison to many of the other—some life-threatening—impacts of climate change, there is nonetheless something fundamental in the cross-cultural appreciation of beer. For perhaps many millennia[45,46], and still today for many people, beer has been an important component of social gatherings and human celebration. Thus, although it may be argued that consuming less beer isn't itself disastrous—and may even have health benefits, there is nevertheless little doubt that for millions of people around the world, the climate impacts on beer consumption will add insult to injury.

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Methods

Framework of integrated model. Our integrated model (frameworks are in Figs. SI-Fig.6 and SI-Fig.7) links Earth System Models (ESMs, including GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M) with a crop model (DSSAT) and a global economic model (GTAP). The ESMs estimate the severity and frequency of extreme events under four scenarios (RCP2. 6, RCP4.5, RCP6.0, and RCP8.5). DSSAT simulates global changes in barley yield during extreme event years. GTAP, which contains a detailed classification of the agricultural and food sectors, simulates the changes in global beer consumption and prices based on barley yield shocks.

Source of historical and future weather data. For historical data (1981-2010), daily weather data come from the AgMERRA dataset. The AgMERRA is a post-processing of the NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA) suitable for agricultural modeling, featuring consistent, daily time series data and the data demonstrates a similar pattern to other observed historical products, and also substantially improves the representation of daily precipitation distributions of extreme events[47]. The data of growth duration and planting region of barley comes from Sacks et al, 2010[48]. For future data (2010-2099), the climate scenario data was extracted from output archives of five ESMs under four Representative Concentration Pathways (RCP2.6, RCP4.5, RCP6.0, RCP8.5) retrieved from CMIP website (http://cmip-pcmdi.llnl.gov/cmip5). The data was interpolated into 0.5°x0.5°horizontal resolution and bias-corrected with respect to historical observation by Hempel et al.[49] to remove systematic errors.

Extreme years selected using earth system models (ESMs).

First, standardized precipitation index (*SPI*)[50] and extreme degree days 30°C+ (*EDD*) are calculated for each grid cell (‘*g*’) and each year (‘*y*’) in global barley planting region during growth period of barley using the historical data from 1981-2010.

Second, the annual global barley drought index (*DI*) is calculated using the following equation based on the standard precipitation index (*SPI*):

$$DI_y = \sum_{g=1}^{n} A_g \times SPI_{g,y} \text{ , } when \;\; SPI_{g,y} \le \text{-1.0} \qquad (1)$$

where DI_y is global barley drought index for year *y*; A_g is the scaling factor equal to the ratio of the area for grid cell ‘*g*’ to total area in global barley planting region; $SPI_{g,y}$ is the standardized precipitation index for grid cell ‘*g*’ and year ‘*y*’; *n* is the total number of grid cells for planting barley.

For extreme heat, the annual global barley heat index (*HI*) is calculated using the similar method based on extreme degree days 30℃+ (EDD). The threshold (30℃) is in accord with the existing literature that temperature exposure in excess of will be harmful to the growth of barley[51-53].

Third, we fit the annual global barley drought and heat indices with Pearson-III distributions (the "best" universal model for describing probability distribution of extreme events[54]; also see K-S test in section 2.2 of SI), and use the fitted curves to derive the global barley drought index DI^{100} and heat index HI^{100} corresponding to 1 in 100 year probability.

Next, using the same method in step 1 and 2 to calculate the global barley drought index (DI_y) and heat index (HI_y) for 4 RCPs and 5 ESMs in the future (2010-2099).

Finally, we select extreme event years when both extreme drought ($DI_y \geqslant DI^{100}$) and extreme heat ($HI_y \geqslant HI^{100}$) concurrently strike in the same year. Then we calculate an integrated extreme event index (EEI_y) for the selected years based on the following equation:

$$EEI_{\mathrm{y}} = \begin{cases} \dfrac{DI_y - DI^{100}}{DI^{100}} + \dfrac{HI_y - HI^{100}}{HI^{100}}, & when\ DI_y \geq DI^{100}\ and\ HI_y \geq HI^{100} \\ -1, & when\ DI_y < DI^{100}\ or\ HI_y < HI^{100} \end{cases} \qquad (2)$$

All modeled extreme event years where $EEI_y \geqslant 0$ are selected to simulate global barley yield using the crop model and subsequently beer supply and price using the economic model (details in SI section 2.2).

Simulation of barley yield change using crop model (DSSAT).

According to the extreme event years selected above, we simulate global barley yield change due to extreme events compared with the average yield during 1981-2010 on gridded level by the CSM-CERES-Barley, which is part of the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.6[55]. The DSSAT-Barley has been tested in various environments around the globe. For example, barley-specific analyses using DSSAT were performed in Czech Republic which shows that the coefficient of determination between simulated and experimental yields equals 0.88[34]; Other applications in Argentine, Central Europe, Ireland and West Asia all provided the reliability of CERES-Barley in different environments with root-mean-square-error (RMSE) for yield less than 15%[35-38]. A Europe-focused model intercomparison also shows that yields projected by the DSSAT model are near the mean of nine crop models[39].

Before feeding into the input database, we adapted the source code of DSSAT for parallel computations at a 0.5°x0.5° grid resolution on High Performance Computers (HPC), and then gridded formatted inputs used to drive the model include daily weather data, soil parameters, crop calendar data and management information:

- Weather data inputs for DSSAT include maximum and minimum temperatures, precipitation, total radiation, and humidity, derived from the sources described above.
- Soil parameters (soil texture, bulk density, PH, organic carbon content, and fraction of calcium carbonate for each of five 20 cm thick soil layers) were obtained from International Soil Profile Data set (WISE)[56]. Soil parameters were allocated to each simulation grid cell based on the spatially dominant soil type taken from the digital Soil Map of the World (DSMW) (FAO, 1990)[57]. Soil retention and hydraulic parameters were calculated using pedotransfer functions[58]. Soil parameters for organic soils missing in WISE data set were adopted from Boogaart et al (1998)[59].
- Crop calendar data set was obtained from the Center for Sustainability and Global Environment (SAGE). This data set is the result of digitizing and georeferencing existing observations of crop planting and harvesting dates, at a resolution of 5'[50]. The data set provides ranges of crop planting and harvesting dates for different crops in each grid.
- Management information requires fertilizer applications, irrigation, and other management practices. A crop-specific gridded data set (by 5') of nitrogen fertilizer application for the world (around the years of 1999 or 2000) was used in our simulation to setup current fertilizer

application rate for barley in each grid cell, with phosphorous and potash assuming unlimited. This dataset was developed by integrating national and subnational fertilizer application data from a variety of sources[5,60,61].

Then we first model barley yields across the world during the historical period (1981-2010). Barley yield was simulated as 0.5°x0.5° grid scale, with two main production systems (spring barley and winter barley; regarding how to select spring and winter barely in each grid, see detail in section 2.3 of SI) and two water management scenarios (fully irrigated and rainfed). Historical national barley production is aggregated from simulated gridded yield, and weighted by grid cell barley areas around 2000 from the gridded global dataset by combining two data products of Monfreda et al (2008)[62] and Spatial Production Allocation Model[63]. Second, we adopted the barley genetic parameters of specific cultivar from pervious works such as Trnka et al., (2004)[34] as the initial parameters. But applying parameters of a few specific cultivars to the whole world is more complicated than it seems, for example, cultivars from Europe may not able to germinate in tropical and semi-tropic conditions and vice versa. As lacking of experimental observation, we tuned and calibrated model parameters related to crop genotype characteristics so that the simulated yields from 1981-2010 were comparable to the statistical data (Figs. SI-17 to SI-19) following the Xiong et al., (2014)[64] method (See detail in section 2.3 of SI). Third, barley yields across the world are simulated during extreme event years. Fourth, global and national yields were aggregated from gridded values. Finally, national/regional and global yield change is calculated, which is the deviation from the national/regional or global yield average of 1981-2010(details in SI section 2.3).

Simulation of beer consumption and price change using a global economic model (GTAP).

The barley yield changes from the crop model are used to carry out simulations using GTAP for changes in barley production and the impact on beer production and price. GTAP is a well-know and widely used global general equilibrium economic model developed by the Department of Agricultural Economics at Purdue University[65,66]. The model assumes cost minimization by producers and utility maximization by consumers. In a competitive market setup, prices adjust until supplies and demands of all commodities equalize. The model and database have been extensively used in areas like climate change, food security policy, energy, poverty and migration, etc.

Our simulations use a comparative static analysis approach to simulate the impact of climate changes on beer supply and prices under current economic conditions (e.g. as in Ciscar et al., 2011[40]; Hsiang et al., 2017[41]). Utilizing current economic conditions has the advantage of minimizing assumptions and model uncertainties related to future economic conditions. For using GTAP model to realize the purpose of the study:

First, we improved the database by splitting barley and beer from existing sectors in the model. Barley was split out from "other grains" sector and beer from "beverage and tobacco" sector using the routines from Splitcom method[67]. In this procedure, the old flows of data both at national and trade level are allocated between the new flows using weights. The national weights include the division of each unsplit user's use of the original split commodity among the new commodities; the division of unsplit inputs to the original industry between the new industries; the splitting of new industry's use of each new commodity. Barley use is mainly shared between feed, food, processing and others (seed, waste, etc.). In our process, we assume that processing is mainly covered by beer production, so we allocate all the “processing” share of barley as input to beer sector. The newly created beer sector is allocated to wholesalers/retailors, restaurants/bars and private household consumption (we got the beer consumed by “food” and other sectors from FAOSTAT[68]. Then the proportion of beer used by “food” sector was allocated to three sectors i.e. “wholesalers/retailors, restaurants/bars and private household consumption” based on the respective share of the original “b_t” sector by these three sectors). The “own use” (defined as self-use of a sector of its own output, e.g., seed used to sow “barley” or electricity used by the “electricity” sector) of barely was taken from the “seed”; for beer the own use was kept to zero as beer doesn’t have self-use. Moreover, we have covered only barley-based beer in our “beer” sector, while the beer produced from other feedstocks (wheat, corn etc.) are placed under “otherbt” sector. Trade shares allocate the original slice of the split commodity into the new commodity for all elements of basic price value, tax, and margin. Finally, we used the RAS method for balancing the newly created database. The values for the national shares matrix were obtained from FAOSTAT[68] (Table SI-1). The trade shares matrix was calculated based on the data from UN Comtrade Database[69].

Second, our sectoral aggregation scheme for GTAP ensures that all the competing and complimenting sectors for both barley and beer are present in the most disaggregated form. For example, for barley, other crops compete for inputs of production and both livestock and households (in addition to beer production) are major users of barley (see SI Appendix Table A1). Beer is consumed locally by wholesalers/retailors (covered in “Trade” sector), restaurants/bars (covered in “Recreational services” sector), and bought by private consumers (represented by the default “Private Households”). For regional aggregation, we kept the details for all the main beer producing, consuming, and trading regions, both in volumetric and per capita terms (see SI Appendix Table A2).

Third, the yield shocks for barley were incorporated into GTAP model via changes in land use efficiency for the land used by barley production in each region (parameter “afe” in Eq. 3), the conventional method for translating yield perturbations into economic models[28, 29, 70]. Land use efficiency affects both price and demand for land in the following two equations.

Equation of Price of primary factor composite in each sector/region (The following equations are in percentage form, same here after):

$$pva_{j,r} = \sum_{k=1}^{n}(SVA_{k,j,r} * (pfe_{k,j,r} - afe_{k,j,r})) \qquad \textbf{(3)}$$

where

j = production commodity (industry) ; r = region; k = endowment commodity
pva = firms' price of value added in industry j of region r
pfe = firms' price for endowment commodity k in ind. j, region r
SVA = share of k in total value added in j in r
afe = sector/region specific average rate of primary factor k augmenting technology change

In the improved model, to reflect the difficulty of substitution between land and other key agronomic inputs like labor and capital, we surveyed the existing literate in this area. The literature shows that in case of sudden events, it is hard for farmers to substitute land with other key inputs for crop production and is reflected by the lower value of the elasticity of substitution between land and the other inputs. Therefore, for barely production in the extreme event years, we choose a fraction of the original value. Specifically, we changed the elasticity of substitution between endowments (ESUBVA, Eq. 4, and SI Fig. 8) for barely to a low level of original value according to previous vast literature (for details see SI section 2.4). Considering the uncertainty of the key parameter, we have further analyzed the sensitivity analysis for the key parameter (SI section 2.5 and 3.5)

Endowment commodities' input to each regions/industries:

$$qfe_{k,j,r} = -afe_{k,j,r} + qva_{j,r} - ESUBVA_j * (pfe_{k,j,r} - afe_{k,j,r} - pva_{j,r}) \quad \textbf{(4)}$$

where

qfe = demand for endowment k for use in industry j in region r

qva = value added in industry j of region r

ESUBVA = elasticity of substitution between capital/labor/land, in production of value added in j

In the original GTAP model, capital and labor can freely move between production activities, while for land and natural resources such movement is largely restricted (Eq. 5, 6; SI Fig.9). By default, different crops can adjust their demand for land within some margin (with transformation elasticity ETRAE= -1). However, under the drought and extreme heat conditions of the real world, people may first want to ensure their food security by expanding the area for staple food crops (like wheat) rather than that of barley, resulting in reduced barley planted area. In this study, we made a less severe assumption that land shares will stay unchanged for barley and other competing crops, considering the total supply of land can hardly expand in short time. While we assume that labor, machinery and other inputs to barley (e.g., fertilizers, irrigation, etc.) can be augmented by increasing the working hours or additional investment. So, in our improved model, the acreage of land used for barley (or any other crops) in the normal year is still used for barley (or any other crops) in during extreme event year (ETRAE = 0).

Allocation of the sluggish endowments across sectors:

$$qoes_{k,j,r} = qo_{k,r} + ETRAE_k * (pm_{k,r} - pmes_{k,j,r}) \quad \textbf{(5)}$$

where

qoes = supply of sluggish endowment k used by j in r

qo = industry output of commodity k in region r

ETRAE = Elasticity of transformation for sluggish primary factor endowments (non-positive, by definition)

pm = market price of commodity k in region r

pmes = market price of sluggish endowment k used by j in r

Composite price for sluggish endowments:

$$pm_{k,r} = \sum_{j=1}^{n} (REVSHR_{k,j,r} * pmes_{k,j,r}) \quad \textbf{(6)}$$

where

REVSHR = share of endowment use by different industries

Mobile endowments (capital and labor) were allowed to behave normally as they can be provided via higher investment under the extreme event (Eq. 7, 8).

Allocation of the mobile endowments across sectors:

$$qo_{k,r} = \sum_{j=1}^{n}(SHREM_{k,j,r} * qfe_{k,j,r}) \quad \textbf{(7)}$$

where

SHREM = share of mobile endowment k used by sector j at market prices

Composite price for mobile endowments:

$$pm_{k,r} = VFM_{k,j,r}/qfe_{k,j,r} \quad \textbf{(8)}$$

where

VFM = Producer expenditure on endowment k by industry j in r valued at market prices

We also add the changes in barley foreign trade to production for each country thereby simulating the changes in barley supply.

Finally, for simulating the changes in beer consumption and price after experiencing the barley production change, we consider regional differences in allocation of barley to all users (beer, feed, food and others). In the normal year, barley shares to different uses come from FAOSTAT[57] (see SI Table 1). In extreme event year, barley is distributed to different users according to the profit maximization principle. Final beer consumption for each country also contains net beer import.

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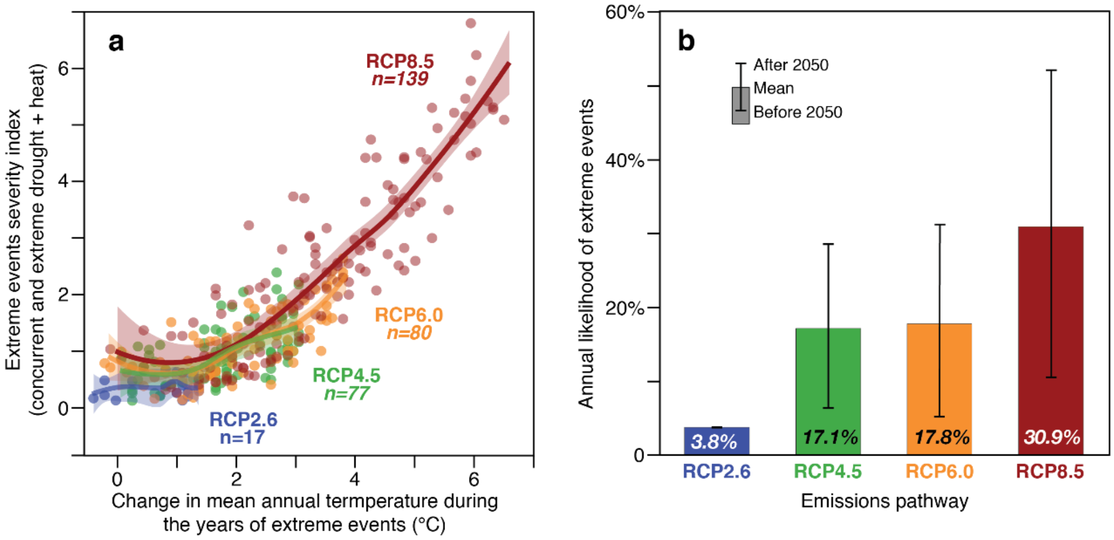

Figure 1 | Extreme event severity and frequency under future climate change. a, The relationship between change in global mean (land) surface temperature in year of extreme event (relative to the mean of observation from 1981-2010) and the severity of concurrent drought and heat, where the curve is binomial regression curve with 95% confidence interval. **b,** Annual likelihood of a concurrent extreme events under each of the Representative Concentration Pathways as projected by five ESM models. Top and bottom whiskers indicate the annual likelihood of extreme events after 2050 and before 2050.

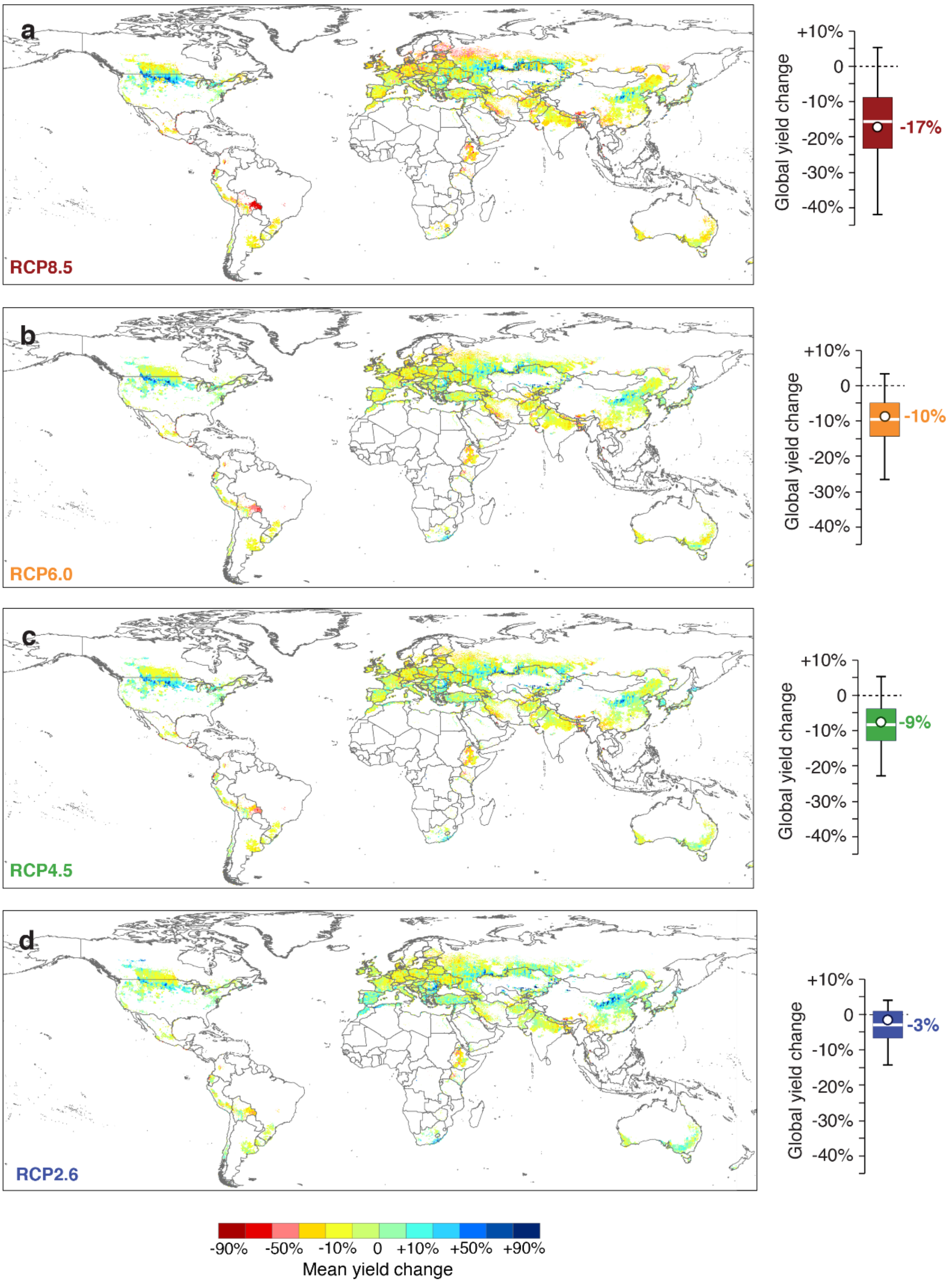

Figure 2 | Average barley yield shocks during extreme event years. Gridded average yield change with 0.5°x0.5° resolution across all predictions of extreme event years (left) and global aggregated change in barley yield (right) under RCP8.5 **(a)**, RCP6.0 **(b)**, RCP4.5 **(c)** and RCP2.6 **(d),** compared with the average yield from 1981-2010. Box-and-whisker plots to the right show the range of global changes, with white points indicating the mean, dark lines indicating the median, top and bottoms of the box at the 25th and 75th percentiles, and whiskers indicating the minimum and maximum of all data. We map all grid cells where barley harvested area exceeds 1% of grid cell area. The grid cell barley areas are from the gridded global dataset around 2000 by combining two data products of Monfreda et al (2008)[62] and Spatial Production Allocation Model[63]

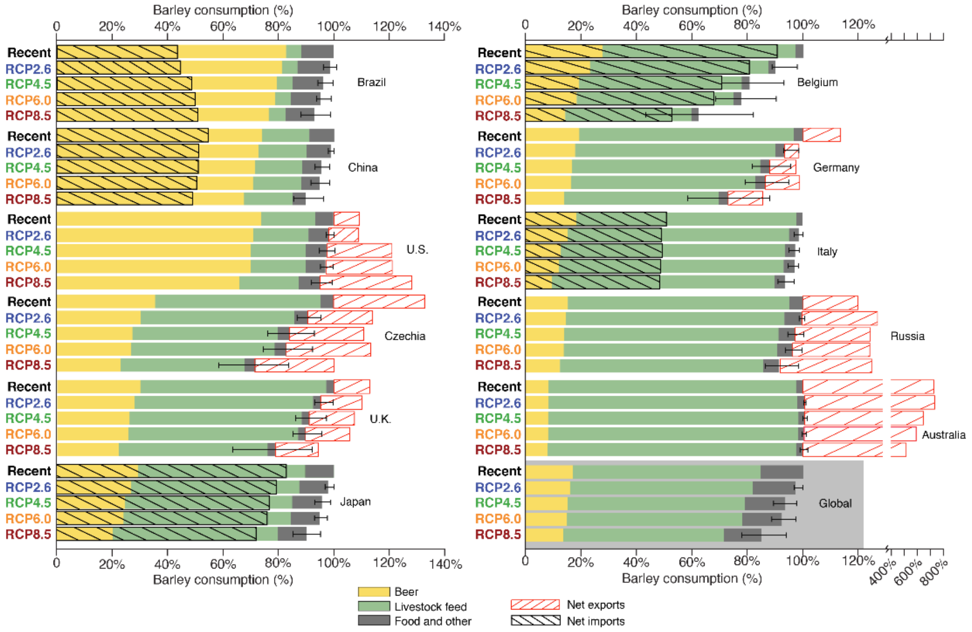

Figure 3 | Barley consumption by country and globally under future climate change. For each country and the global aggregate, the bars show the total consumption of barley averaged over all extreme event years during 2010-2099, and the share for different barley uses. Whiskers indicate the 25th and 75th percentiles of all total consumption changes. Hatching indicates the fraction of consumption imported on net (black) and production exported on net (red), if any. The source of the share in recent year is GTAP database. Here the selected countries are a mix of countries having one or more of significant barely export, import and/or countries with large barley production/consumption. Figs. SI-24 and SI-25 show the 'absolute' and 'relative' share for all the countries.

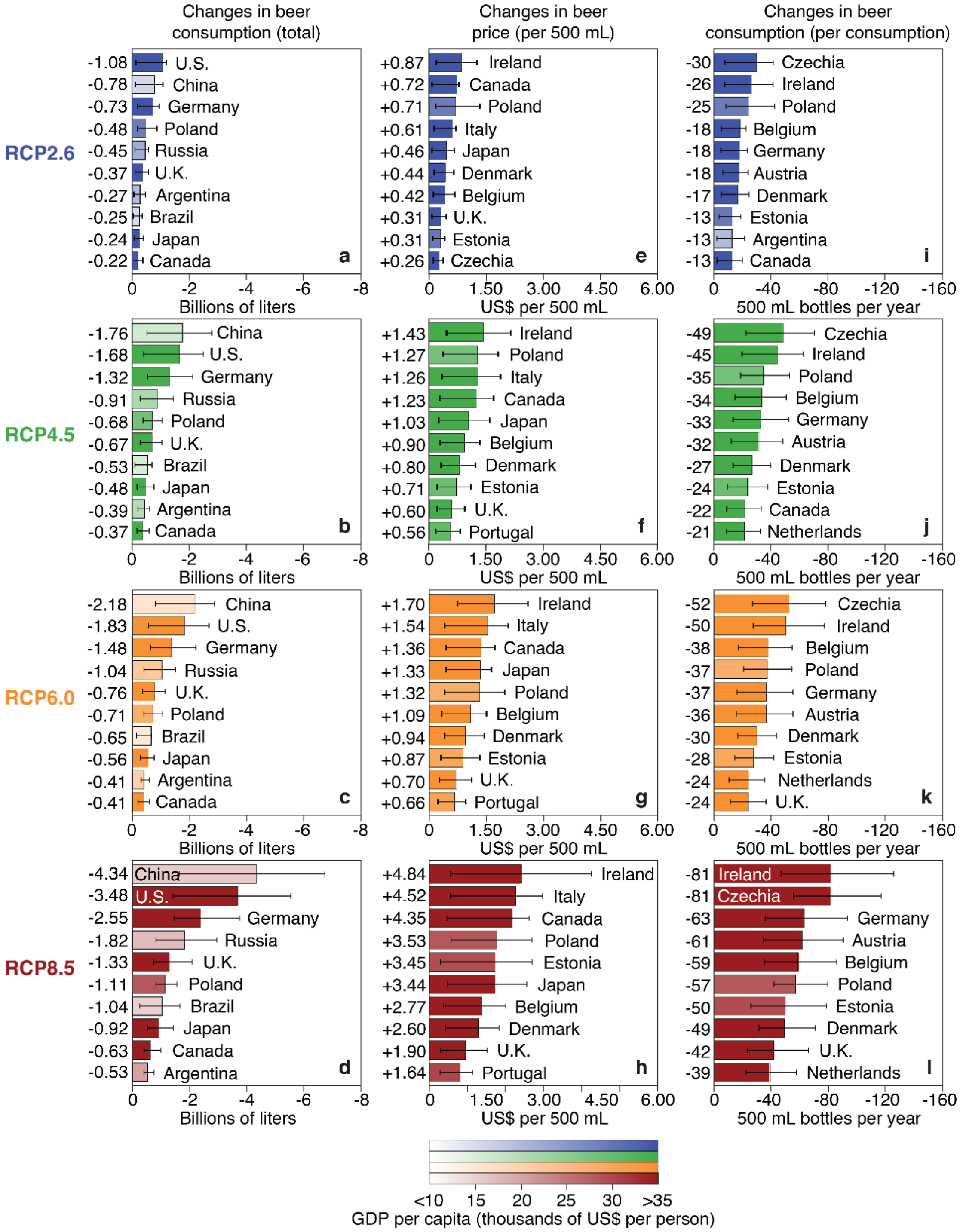

Figure 4 | Changes in beer consumption and price under increasingly severe drought-heat events. Each column of figures present results for top 10 most affected countries i.e., (**a-d**) by absolute change in the volume of beer consumed, (**e-h**) US$ change in beer price, and (**i-l**) beer consumption per capita per annum. The severity of extreme events increases from top to bottom. The length of the bars for each RCP show average changes of all modeled extreme event years 2010-2099. Whiskers indicate the 25th and 75th percentiles of all changes (See percent changes with full range for all main beer consuming countries in Figs. SI-26 to 28; absolute changes in Figs. SI-30 to 32).

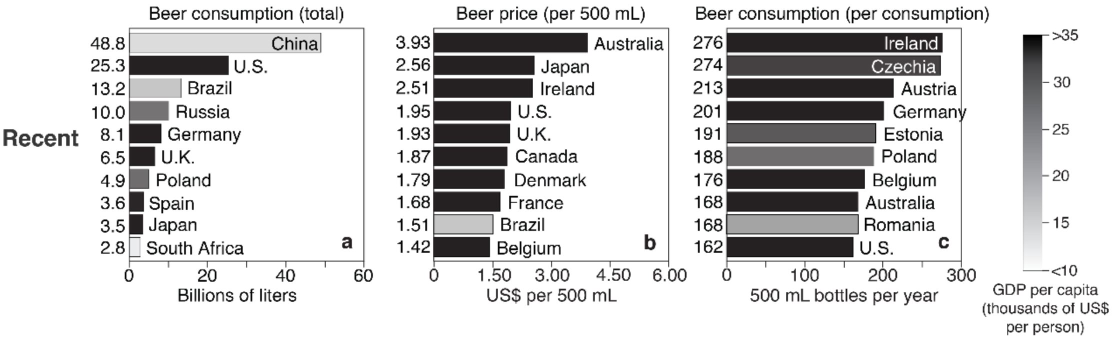

Figure 5 | Beer consumption and price in recent years. The data source of total beer consumption and population is FAOSTAT[68]. The beer price is collected from Numbeo’s survey of cost of living (www.numbeo.com).