Abstract

Globally, India's population is among the most severely impacted by nutrient deficiency, yet millions of tonnes of food are lost before reaching consumers. This study quantifies energy input to reduce grain storage losses across India. In doing so we identify and explore links between SDG2, SDG7, and SDG12, and provide insight for development of joined up agriculture and health policy in the country. Across food groups, grains represent the largest share of daily calories and overall losses by mass in India. Analysing rice, wheat, maize, bajra, and sorghum, we quantify one route to reduce losses in supply chains, by modelling the energy input to maintain favourable climatic conditions in modern silo storage. We quantify key nutrients (calories, protein, zinc, iron, vitamin A) contained within these losses, and calculate roughly how much deficiency in these dietary components could be reduced if grain losses were eliminated. In India, a quarter of losses occur in the storage stage of the supply chain. Our modelling indicates, with appropriate uncertainty, maize has the highest energy input intensity for storage, at 110 kWh per tonne of grain (kWh/t), and wheat the lowest (72 kWh/t). This represents 8%-16% of the energy input required in grain production. We estimate if grain losses across the supply chain were saved and targeted to India's nutritionally deficient population, average protein deficiency could reduce by 46%, calorie by 27%, zinc by 26% and iron by 11%.

Keywords:
Food loss; SDG; energy; hunger; grain storage; India

1 Introduction

India has among the highest rates of child protein-energy malnutrition in the world (Bhutia, 2014). This nutritional challenge extends to micronutrients – i.e. vitamins and minerals – where deficiency in India's population, termed hidden hunger, is among the most severe globally (Muthayya et al., 2013). And yet, an estimated 65 million tonnes (Mt) of food is lost annually before reaching consumers, at an economic cost of approximately US $15 billion in 2014 prices

(Jha et al., 2015). Here, we follow the FAO's definition of food loss, which refers to food intended for consumption, but which is lost during the supply chain from harvest up to the point of retail. This is distinct from food waste, which is the reduction in food due to the actions and practices of retailers, service providers and consumers.

Food loss and waste are not confined to countries such as India, but rather, pose a universal problem. Globally, food that is lost or wasted amounts to 25-30% of all production, and is responsible for 8-10% of global emissions (IPCC, 2019). There is also substantial impact on biodiversity, water and land use (FAO, 2014). Direct economic costs of food loss and waste are an estimated $1 trillion annually, even before accounting for associated social and environmental costs (FAO, 2014). For context, the World Bank puts the total value of the global food system at roughly $8 trillion (World Bank, 2019).

Food loss results in an unproductive allocation of resources that could otherwise help ensure the population receives adequate nutrition and improve food security. However, the relationship between food loss, nutrition and their solutions, including energy, is not fully understood.

Focusing on five major types of grain (rice, wheat, maize, bajra, sorghum), the largest consumption *per capita* food group in Indian diets (Alae-Carew et al., 2019), we examine one route to realise this loss reduction, looking at energy input to control ambient conditions for effective storage of grain in modern silos. We then briefly look at how grain losses may evolve under different Shared Socioeconomic Scenarios (SSPs) in the absence of measures to reduce them. Finally, we quantify the embedded nutrition (calories/energy, protein, iron, zinc, and vitamin A) contained within these losses and, to a rough approximation, estimate how eliminating grain losses across the supply chain may reduce average population deficiencies.

Formally we ask: What role does energy have in the storage component of grain losses? How substantial is this compared to the energy to grow grain crops? To what extent can eliminating food grain loss in India address nutrient deficiency among its population? We provide new insights on previously understudied relationships, and draw conclusions for policy, informed by a systems approach to food, health, and energy. This study contributes to the understanding of interactions between the Sustainable Development Goals (SDG), specifically links between ‘zero hunger’ (SDG2), ‘affordable and clean energy’ (SDG7), and ‘responsible production and consumption’ (SDG12) in the context of food loss. In doing so, this study offers empirical evidence for energy input to reduce grain storage losses for the case of India, and with it, a method applicable to other geographies where food loss is prevalent. Further, it quantifies food loss by way of its potential to address population nutrient deficiencies, thereby highlighting the challenge in human relatable terms.

1.1 Food loss

A recent Food and Agricultural Organization (FAO) report into food loss and waste reduction found that total losses can be over 20% across the supply chain in Central and Southern Asia (FAO, 2019). Within this region, grain supply chain losses in India are often far lower than this on a per cent basis (around 5% is typical). However, we focus on this country for two reasons. Firstly, Indian food loss data is more comprehensive and of better quality than many other economies, for illustration, 55% of all data observations in the FAO’s latest food loss and waste meta-analysis are from India. Secondly, with India’s population size, the absolute magnitude of losses far outweighs many other countries which may have higher per cent losses.

Sources of food loss vary by country and crop or produce, but broadly speaking, for grains this includes pests, rodents, mould and respiration. The main drivers that enable these sources to proliferate are insufficient or non-existent equipment and infrastructure and a lack of training and education on best practice. Energy has been identified as one solution to tackle these drivers and sources of loss, for example, allowing grain to be dried and cooled in climate-controlled silos rather than outside, open to the elements (FAO, 2016).

Within the food loss and waste literature, studies have explored conceptual synergies between reducing food loss and waste and improving public health, including nutrition (Lindgren et al., 2018; Neff et al., 2015). Other studies have quantified this explicitly, for example, from the perspective of food waste and dietary nutrition in the USA (Conrad et al., 2018; Spiker et al., 2017), or seafood loss and the potential recovered nutrition, also focusing on the USA (Love et al., 2015). These studies point to the importance of tackling the dual challenges of malnutrition while minimizing the environmental impacts of diets and food systems. Reducing food loss and waste has a key role to play, but realizing the potential requires interventions that cut across technological, economic, social and behavioral domains.

1.2 Energy in reducing food grain losses

We focus on one such reduction strategy, the role of energy in the storage component of food grain loss. Although not considered perishable in the same way as fruit, vegetables and animal produce, grains are nonetheless highly susceptible to ambient conditions. Food grain loss in storage is in large part driven by unfavorable (normally too high) humidity and temperature (Kumar and Kalita, 2017). This encourages mould, insect propagation, and grain respiration, which all lead to quantitative loss. Controlling these conditions via energy input can mitigate or eliminate these drivers of quantitative storage loss. Another type of loss, termed “qualitative losses” can also occur during storage. These losses include physical damage and a deterioration in taste and appearance, but the grain may still be deemed fit for consumption. We do not consider the latter type of losses in the analysis.

In India, up to 25% of total grain losses can occur during storage (Jha et al. 2015). Most grains are either stored on-farm using small-scale traditional methods, or in centralised depots where it is bagged and kept in outdoor ‘cover and plinth’ (CAP) structures, or indoor warehouses known as *godowns* (Sharon et al., 2014). Currently, very little grain is stored in modern silos which can minimise losses but require energy input to operate effectively. Recognising the need to improve the supply and distribution of grain, there are efforts by the Indian government and the private sector to develop modern silo infrastructure (10 Mt of new capacity over 2016-2020). Focusing on energy input, we estimate the energy required to reduce losses related to drying and storage of major grains in India. Specifically, we modelled the useful energy per tonne of grain to initially dry and cool produce after harvest, and then maintain necessary storage conditions over a range of likely timeframes.

Energy input is determined by many factors including temperature, humidity and the biophysical properties of different grains. A key factor is the moisture content of grain, i.e. the proportion by mass of water. The energy required to remove a unit mass of water increases as moisture content decreases. That is, as grain dries it becomes progressively more energy intensive to further remove water. To prevent losses, grain must be stored at moisture levels as low as 12% (Directorate of Marketing & Inspection, 2005) but field maturity is far higher than this, commonly harvested at levels of 18% to 30% (see Table 1 and Table A.1 in 6 Appendix). Alongside this drying component, we construct a model of the cooling and maintenance requirements of grain for storage, using data from empirical and industry literature to parameterise the model (see section 2.1 Modelling energy in grain storage losses and 6 Appendix).

Parameter	**Rice**	**Wheat**	**Maize**	**Sorghum**	**Bajra**
Harvest mc high (%)	28	22	30	25	22
Harvest mc low (%)	20	18	23	20	18
Storage mc high (%)	14	14	14	14	14
Storage mc low (%)	12	12	12	12	12
Storage temp. high (°C)	15	15	15	15	15
Storage temp. low (°C)	10	10	10	10	10

Table 1: Moisture and temperature parameters for the energy model. See Table A.1 in Appendix for sources.
* mc = moisture content

1.3 Nutrition

Addressing grain loss in principle enables additional nutrient supply to be directed toward India’s population. The importance of the five nutrients quantified in this study are briefly detailed. Protein is an key dietary component, and deficiency contributes to severe health outcomes, including limiting growth, stunting among children, and immune system complication (Wu et al., 2016). In extreme cases, energy-protein deficiency can progress to energy-protein malnutrition which is associated with severe immune deficiency, muscle atrophy and early death (Müller and Krawinkel, 2005). Within micronutrients, iron, zinc and vitamin A are among the most prevalent micronutrient deficiencies globally (Muthayya et al., 2013). Iron deficiency reduces cognitive function and increases risk of anemia during pregnancy (Lynch, 2011), zinc deficiency impairs growth and the efficacy of several vital organ systems (Roohani et al., 2013), while a severe lack of vitamin A is a leading cause of blindness among children (Akhtar et al., 2013). Given the prevalence of these deficiencies in India, we build on previous work from Rao et al. (2018) and quantify the potential increase in the supply of these nutrients should losses of rice, wheat, maize, bajra and sorghum be eliminated.

A recent study looking at the availability of macronutrients (calories, digestible protein and fat) found that the nutrient supply gap could be narrowed, but not resolved, under scenarios of reduced food loss and improved yield (Ritchie et al., 2018). We investigate a similar problem area, extending to micronutrients but limiting the analysis to grain losses. The main thrust of this study is to understand the role of energy in grain losses, however, given some similarity in the food loss-nutrition component, we now briefly discuss the methods.

Ritchie et al. (2018) use FAO nationally aggregated production and loss statistics across major crops and commodities, and apply regional (South Asia) estimates of supply chain stage losses to India. Lost macronutrients of interest are quantified across each stage and apply a log-normal distribution to quantify the proportion of the population that could receive the recommended share. We take a bottom-up approach, using district level production and disaggregated, sub-national food loss survey data. Total potential additional supply is calculated on a district basis and aggregated at state and national level. We assume that all the nutrition within the lost grain, factoring in the proportion that is not directly consumed, is distributed to the population. Rather than assuming a log-normal distribution, we contextualise the increased nutrition achieved through saving lost grain by comparing against estimated population nutrient deficiencies derived from National Sample Survey data.

2 Materials and Methods

2.1 Modelling energy in grain storage losses

A physical modelling approach was used to quantify the energy required to dry and cool food grain from harvest, and then maintain conditions for storage. Total energy was modelled as the sum of these three processes. The model makes use of equations for sensible heat (for cooling) [Eq. 1] and latent heat (for drying) [Eq. 2] and biophysical and agricultural properties of the different grains.

$$E_{sensible} = m \cdot c \cdot \Delta T \ (J), \qquad [Eq. 1]$$

where m is the mass of grain (kg), c is specific heat capacity (J kg^{-1} °C $^{-1}$), and ΔT (°C) is the difference between harvest and grain storage temperature.

$$E_{latent} = m \cdot \Delta MC \cdot h_s \ (J), \qquad [Eq. 2]$$

where m is mass of grain (kg), ΔMC is the difference between the moisture content of grain at harvest and that during storage, and h_s is the differential heat of sorption (kJ/kg), which is the energy to remove a unit mass of water (see Figure A.1). This component is comprised of the sum of the latent heat of free water and differential heat of wetting, which is unique for each grain type and changes as a function of moisture.

Literature shows that different types of grain have heterogeneity across moisture content at harvest, and differ in the energy required to remove a unit mass of water from the grain (see Figure A.1). The bulk property of cereals makes them good insulators, and properly stored grain retains its temperature and moisture content once cooled and dried. However, possible extended storage duration and India's climate necessitate maintenance of temperature and moisture conditions. This requires additional energy input which we model based on parameters developed from a stylised duty cycle from Indian industry literature (Graintechnik, 2019, 2018). Simply, this takes power output and a coefficient of performance of a grain silo chiller operated under typical Indian conditions and models the energy requirements based on the intensity of use (hours per day, day per year) given by the industry specific duty cycle.

A Monte-Carlo analysis was performed to sample parameter values under a uniform probability distribution. Parameter values were drawn from scientific studies or government standards specific to India, and not constructed with directly observed and spatially resolved data. Upper and lower bounds of all the main parameter values and their sources are given in Table 1, Table A.1 and Table A.2 in the Appendix. Where no range of values could be found, we varied a single parameter value to give plausible upper and lower bounds - see Appendix Table A.1 and Table A.2 for details.

Safe grain storage temperatures to minimise losses from insects, mites and fungi (including mycotoxins) are in the region of 15 °C (HGCA, 2011) to 10 °C (Sawant et al., 2012). Common insect species found in stored grain cease reproduction around 13 °C (Manandhar et al., 2018). Here, we set an upper bound at 15°C and lower bound at 10°C.

Values for storage moisture content of grains were sourced from post-harvest grain profiles of India's Ministry of Agriculture and Farmers Welfare, Directorate of Marketing & Inspection (DMI) (2005). These profiles outline best practice and standards for the quality, storage parameters and nutritional profile of India's marketed grain. Values for bajra were sourced from a recent report by the Indian Institute of Millets Research (Chapke et al., 2018).

For grain, the latent energy (reducing moisture content) component is typically larger than sensible energy (reducing temperature), and, as has been described, the model uses grain specific data for harvest conditions and differential heat of sorption. Some additional effort is given to describing how these elements are characterised in the analysis.

Energy-moisture content relationships are different for each grain type, and is typically determined experimentally (e.g. through static or dynamic gravimetric methods). Two studies were selected from literature that provided differential heat of sorption data for the five grains of interest. Four (rice, wheat, corn/maize, sorghum) came from a study by Cenkowski et al. (1992). Data for pearl millet (bajra) was obtained from Singh et al. (2011). The former was selected as a source as it had the most comprehensive coverage of required grain data of the studies assessed. The latter was selected for being specific to India. The differential heat of sorption curves for each grain are given in Figure A.1. In the model, a sampled harvest moisture content (from bounded upper/lower values) and storage moisture content form a definite integral which is then evaluated.

2.2 Grain losses

Average district level crop production data were calculated for the period 2010-2014, from published Indian government statistics (Directorate of Economics & Statistics, n.d.). We are concerned with grain production for human consumption and the losses involved in this portion of supply, not that which is diverted for animal feed or as residual produce (broken and damaged grains, i.e. qualitative losses). Therefore, district level production statistics were modified by a factor for the proportion of each grain type that are consumed by humans directly, using data from the US Dept. Agriculture (USDA) annual grain assessment on India (USDA, 2019). The USDA does not disaggregate between feed and residual in the data, so it was not possible to see their individual split. For wheat, sorghum and bajra, animal feed and residual typically make up ~5% of total supply (USDA, 2019). Maize is different, in that a substantial proportion of production (~50%) is used as animal feed and for use in industrial processes (USDA, 2019). No adequate data for rice could be found, and so was assumed to have zero supply diverted. Excluding these components is necessary for two reasons. Nutritionally, feed and residual grain are not directly consumed by humans, and secondly, we are concerned with the quantitative not qualitive loss i.e. the measurable reduction in mass of grain. Finally, it was assumed that 100% of grain was edible.

2.3 Nutrition

Nutrient composition of grains and recommended daily allowance (RDA) were sourced from the National Institute of Nutrition, India – see Table 2 and Table 3. Values for RDA were standardised to one equivalent consumer unit (CU), a metric developed by the Indian Council of Medical Research to equate the nutritional needs of women, men and children. One CU represents the daily nutritional need of a sedentary 60kg man. Women, children and other profile types for men are adjusted by a coefficient that reflects a greater or lesser daily requirement.

Grain	**Calorie (kCal/kg)**	**Protein (g/kg)**	**Iron (mg/kg)**	**Zinc (mg/kg)**	**Vitamin A (mcg/kg)**
Rice	3564	79.4	6.5	12.1	80
Bajra	3480	109.6	64.2	27.6	330
Maize	3341	88.0	24.9	22.7	80
Sorghum	3341	99.7	39.5	19.6	118
Wheat	3203	105.7	41.0	28.5	73

Table 2: Nutrient composition of major grains. Source: (Indian Council of Medical Research, 2017)

Nutrient	**Quantity**	**Unit**
Calories	2320	kCal/day
Protein	60	g/day
Iron	17	mg/day
Zinc	12	mg/day
Vitamin A	600	mcg/day

Table 3: Recommended daily allowance (RDA) of one equivalent Consumption Unit (a sedentary 60kg man). Source: (Indian Council of Medical Research, 2009)

The primary source of Indian food loss data in this analysis was a study by the Indian Council of Agricultural Research (ICAR), see Jha et al. (2015) for details on the survey methods and analysis. Survey results were compared with aggregate FAO statistics (see 3 Results and Discussion).

Each district's grain production was mapped to one of 15 agroclimatic zones in India, the resolution of the food loss survey data. All districts in a given zone were assigned the same loss proportions for crops and supply chain stages, but varied in their production data. Where loss data of a given grain and region was absent, but data showed production exists, that district was assigned a loss rate at the national level from the survey.

With RDA and food nutrition values, we calculated, at the state and national level, the calories, protein, vitamin A, iron and zinc contained within lost grain, giving an upper limit on possible increased supply should losses be eliminated. These are then attributed to estimated average nutrient intake of India's nutrient deficient population to approximate the potential improvement in population nutrition. These estimates are as calculated in Defries et al. (2018) and Rao et al. (2018) from consumption expenditures in India's National Sample Survey (2011–12). Nutrient deficiency is a useful way to contextualise grain losses, but the analysis employed here must be caveated to make clear its limitations. Foremost, population deficiency calculations are state-level averages derived from household food expenditure survey data, that masks granularity and heterogeneity in dietary intake. See Defries et al. (2018) for detailed discussion on the limitations of this method.

A high-level analysis was conducted to examine the possible scale of grain loss if rates remained constant but production increased alongside population. This was calculated by applying Indian population projections in the Shared Socio-economic Pathways (SSPs). The SSPs are a set of five pathways that model how key socioeconomic factors may impact energy demand and CO2 emission trajectories over this century (see Riahi et al., 2017). They are based on five narratives of global socioeconomic trends, of which three are used here. These are SSP1 - spanning 'the green road' of a shift to a sustainable world, SSP2 - 'middle of the road' representing business as usual, and SSP3 - 'a rocky road' of regional rivalry (SSP3). See O'Neill et al., (2017) for further details.

3 Results and Discussion

3.1 The role of energy in reducing grain storage losses

We find that the energy to provide suitable storage conditions is largely dependent on the harvest moisture content and intrinsic biophysical properties of the grain. Figure 1 shows a probability density distribution of energy input intensity for each grain to deliver favourable climatic conditions for safe (minimal loss) storage. The distribution was generated by Monte Carlo analysis of sampled (n=100,000) model parameter values. Sample number was determined by looking at the convergence of the mean value of rice over a logarithmic range from 10 to 1,000,000 model runs. Mean value gave adequate convergence (0.001% difference) between 100,000 and 1,000,000, and so we use the former number.

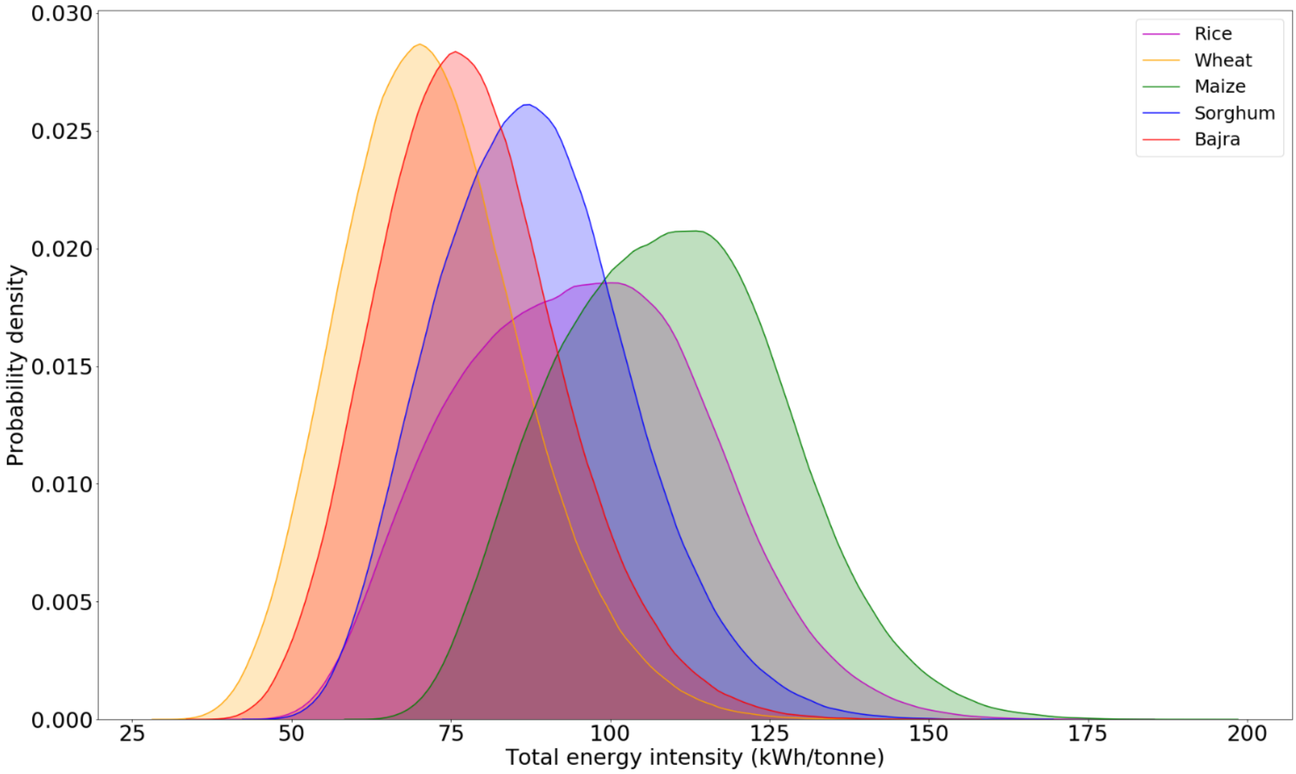


Figure 1: Probability density distribution of energy input intensity required to enable climatic conditions for effective grain storage.

The distribution for wheat (orange-yellow curve) has the lowest mean energy intensity-standard deviation in parenthesis-at 72 (14) kWh t^{-1} (furthest to the left in Figure 1), followed by bajra (red) at 78 (14) kWh t^{-1} and sorghum (blue) at 88 (15) kWh t^{-1}. Maize (green) has the highest mean energy intensity - 110 (18) kWh t^{-1} - followed by rice (purple) at 96 (19) kWh t^{-1}. These two grains also display the largest distributional variance, reflecting the broader range of literature values for harvested moisture content than for the other grains.

To put this into context, we compare against previous work that looked at energy input intensities to grow and produce the same set of grains in India (see Rao et al., 2019 for details). Figure 2 shows these two energy components for each grain. Values modelled in this study are given in orange with error bars at the 10th and 90th percentiles from the Monte-Carlo analysis shown in Figure 1. Depending on the grain, the mean useful energy for storage constitutes an additional 8% - 16% of input on top of that used in production.

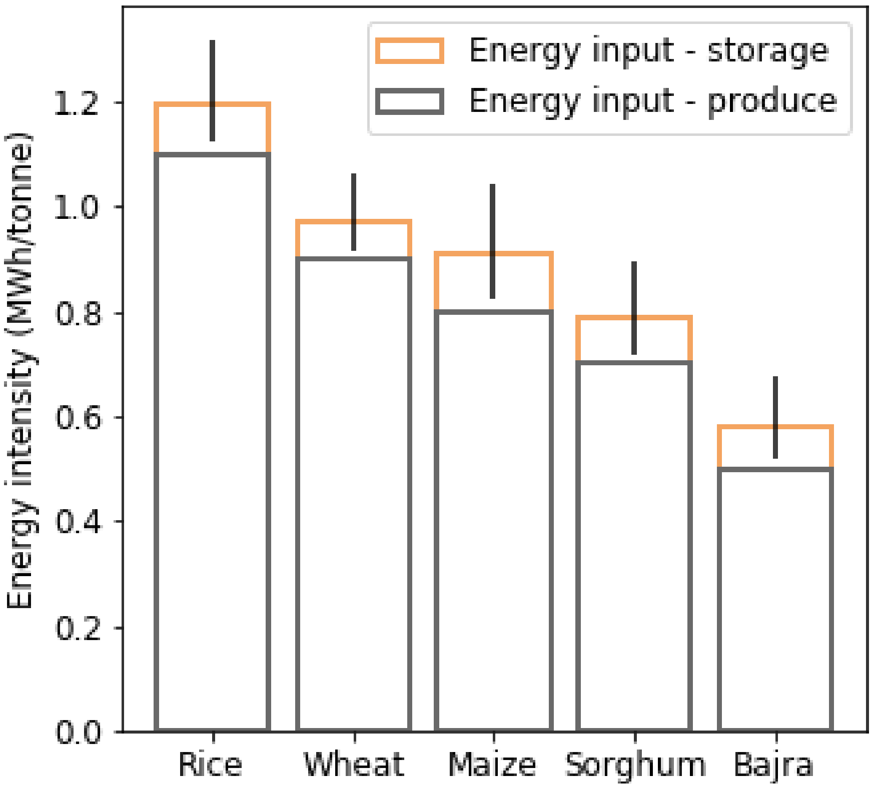


Figure 2: The additional energy required to minimize grain storage losses compared to energy input demands in producing a tonne of grain. Energy input values for production are sourced from Rao et al., 2019. Storage energy input shows modelled mean values with 10th and 90th percentiles as error bars.

This finding highlights the possible energy trade-off in reducing India's grain losses. Previous studies also investigate a similar trade-off, looking at environmental impacts of developing cold supply chains to reduce food losses (Heard and Miller, 2019, 2016). The increased energy requirement could be compensated by improving production efficiency, or as studies have explored, shifting some production of rice to less energy intensive cereals (Davis et al., 2019; Rao et al., 2019, 2018). Further, some of this input is mitigated by resulting reduced grain losses, which ultimately manifests in more grain supply and the energy and nutrients therein.

Energy for grain storage is not the only 'cost' involved in tackling supply chain losses, another being the economic investment required, for example, in developing silo infrastructure, and operation and maintenance costs thereafter. Capital costs for a typical 50,000 tonne silo (normally 4 x 12.5 kt silos) in India have been estimated at Rs. 31 crore (approximately $4 million) (World Bank, 2013). More recently, evidence on completed and ongoing projects from India's Department of Economic Affairs suggests costs of around Rs. 35 crore. Running costs of energy input are determined by a number of factors, tariff structure, geography, prevailing climate conditions and so have not been explicitly considered here. However, indicatively, average power prices across India over 2017-18 were Rs. 7.54/kWh and Rs. 8.69/kWh for industrial and commercial consumers respectively (Power Finance Corporation, 2020). Nonetheless, it is insightful from a scientific and policy perspective to develop our understanding of interlinkages within food systems, even if constrained, as here, to a single main food type.

3.2 Food grain loss data

Table 4 summarises the annual production, average loss rate and annual loss quantity for each grain studied. Rice and wheat dominate production for direct human consumption, with a combined 176 Mt or 88% of total production of the five grains considered. Through the supply chain, this translates to 4.1 Mt and 4.6 Mt of losses for rice and wheat respectively. Across grains, sorghum has the highest national average loss rates (6.0%), followed by rice (5.5%) and bajra (5.2%). Wheat and maize have the lowest loss rates on average from the survey, at 4.9% and 4.7%.

Grain	**Annual production (Mt)***	**National av. loss rate (%)**	**Annual loss (Mt)†**
Rice	87.5	5.5	4.1
Wheat	88.6	4.9	4.6
Maize	9.7	4.7	0.4
Bajra	9.4	5.2	0.5

Sorghum	5.0	6.0	0.3

*Table 4: Average food loss rates and annual tonnage of major grains from harvest to pre-retail. Source: production – Ministry of Agriculture and Farmers Welfare, loss rates – Jha et al., 2015. *average production over 2010-2014 and excludes production not for direct human consumption. † annual loss reflects regional rather than national average loss rates and accounts for adjusted production figures.*

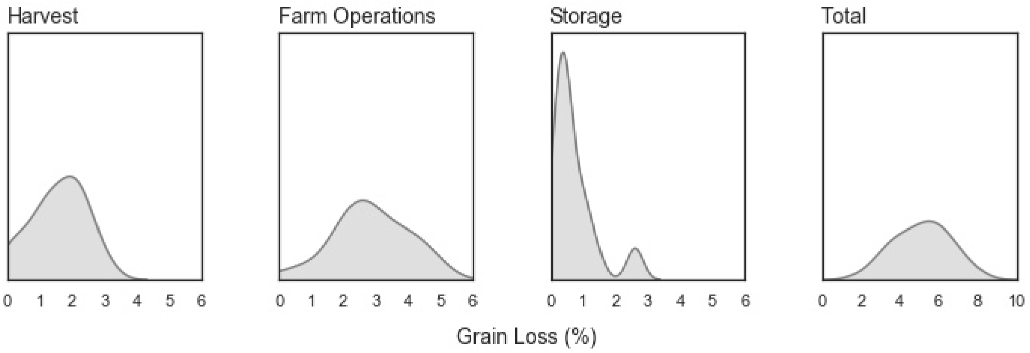
Variation in loss rates presented in Table 4 can be attributed to two main reasons. Grain production tends to be regionally concentrated, with rice focused in the east and coastal south, and wheat in the north west. Bajra is grown chiefly in the west and parts of the south, while maize and sorghum are produced in the central regions. Punjab and Haryana, two north-western states, have experienced agricultural mechanisation, which is one possible reason why total loss rates for wheat are lower than some other grains. Another reason is the monsoon and general climate variability and the effect on losses. An early or late monsoon, and its magnitude, plays a role in grain losses across harvest, processing and storage.

Looking across all the major food groups and crops surveyed, Eastern Plateau and Hills (Chhattisgarh, Jharkhand, Odisha), and Central Plateau and Hills (predominantly Madhya Pradesh) are two regions had, on average, the highest loss rates. Reasons for this are unclear, but predominant crop type and poverty prevalence are two possible factors. The latter as these two regions encompass some of India’s most deprived areas. At the other end, the Western Dry Region (most of Rajasthan and some neighbouring areas) and Trans Gangetic Plain (Punjab and Haryana) had the lowest loss rates. Local climate is one likely factor here, but the aforementioned mechanisation could also be helping to lower losses.

The survey data (Jha et al. 2015) reported here was conducted over a single year and so the data is susceptible to annual climate variation on the Indian sub-continent. Indeed, an initial 2012 benchmark survey produced different loss rates among grains to this more recent data, but still within the range of 4%-6% (Nanda et al., 2012).

The distribution of grain losses at each major supply chain stage (harvest, farm operations, storage) and a combined total is shown in Figure 3. Figure 3a gives a distribution of loss rates for survey observations across all grains. Figure 3b shows box plots of the distribution of percentage losses for each grain within each stage. Harvest and farm operation stages account for the bulk of losses for all five grain types, but also display high variance in loss rates (Figure 3a). Storage accounts for a smaller proportion of grain losses and there is less variability across grains and regions.

a) Loss distribution all grains



b) Loss rates by grain

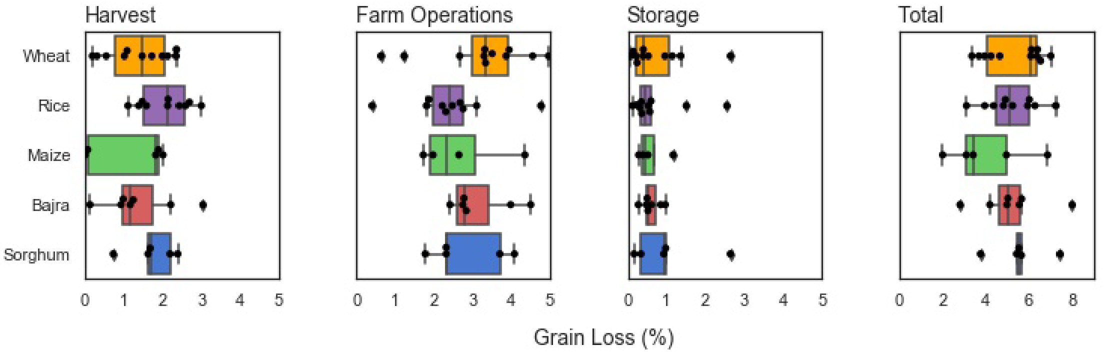


Figure 3: The distribution of grain losses at each major supply chain stage. The top panel (a) gives a combined distribution of loss rates for all the grains. The bottom panel (b) gives box plots of each of grain studied. Each observation (wheat – n=11, rice – n=10, maize – n=5, bajra – n=7, sorghum – n=5) represents a mean value from one of the 14 mainland agro-climatic zones of India. Source data from Jha et al., 2015.

There is little empirical and robust data on food losses among different groups, regions and supply chain stages. Data for this analysis was sourced from the most comprehensive survey of food losses in India to date. However, some survey data were self-reported by farmers rather than directly observed, and aggregate loss rates did not wholly align with FAO national figures. We used the ICAR survey (Jha et al. 2015) rather than FAO figures due to the granularity and heterogeneity of data, and its largely observed rather than modelled component. This highlights a general issue of the availability and efficacy of data, indeed, globally only 4.4% of FAO food loss factors are actually reported rather than estimated or modelled (FAO, 2018). The data gap within food loss and waste, especially for emerging economies, has been identified as a barrier to effective policy formation (Xue et al., 2017). More broadly, data challenges across food systems have been recognised in the IPCC's report on climate change and land (IPCC, 2019).

3.3 Framing future grain loss trajectories

Section 3.2 looked at the current state of food grain losses in India, and section 3.4 extends this to understand the scale of additional nutrient supply should these losses be addressed. To frame this, we first explore, in simple terms, how grain losses could develop in the absence of concerted action. In particular, highlighting possible trajectories out to 2030, the delivery year for many Sustainable Development Goals.

There is limited quantified, spatially resolved data on projected changes to India's agricultural production. Nonetheless, it is valuable to understand how grain losses may evolve in the future. We explore simple scenarios of future grain losses under different population projections taken from three Shared Socioeconomic Pathways (SSP1, SSP2, SSP3) (see Figure A.2 in the Appendix).

By 2030, under a trajectory with no significant measures to address the problem, losses from grain intended for human consumption could increase by about 10% - 20% to reach 11.2-11.8 million tonnes per year, under the assumption of population driven production increases. Correspondingly, relevant Sustainable Development Goals target a 50% reduction in food waste and efforts to reduce food losses (SDG12.3) and aim to eliminate malnutrition and enable all people to access nutritious foods (SDG2.1-2.2). In India achieving these goals will require a host of technical, socio-economic and policy actions, many of them non-trivial. Reform of the country's food subsidy programme is one element of this and is often the subject of debate. A joint report by the ICRIER and OECD discussed measures to overhaul of the Public Distribution System (PDS), that would deliver better health, wellbeing and economic outcomes (OECD, 2018). The nature of these issues leads their politicization, especially in regards to the PDS. We opt to explore an adaptive solution, modernisation of silo infrastructure, a step that will not fundamentally alter, but could improve, India's food system.

These simple loss projections are caveated in that dietary shift and changes to the import/export balance are not considered. However, a recent review of future diet projections in India, found per capita rice and wheat consumption is forecast to remain fairly stable, meaning total consumption may broadly increase with population (Alae-Carew et al., 2019).

3.4 Improved supply from eliminating grain losses – addressing nutrient deficiency

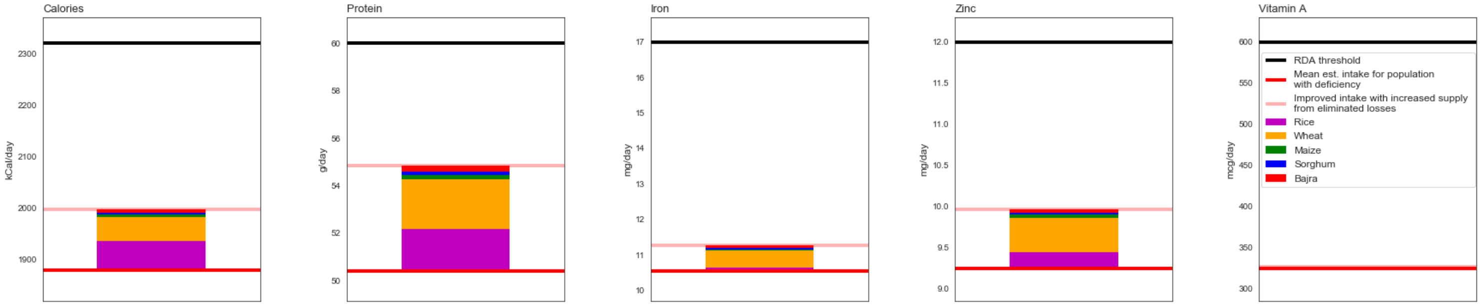
In addressing grain losses, the benefit is realised either in reducing resource inputs to provide the same level of net nutrition, or, the same level of resource input for additional nutrient supply. We study the latter case, owing to known deficiency in key nutrients within Indian populations. However, we briefly contextualise these losses for the prior case of reducing resource inputs and environmental costs. Applying data from previous studies on Indian grain production to that of the calculated losses for each grain type and each district (Rao et al, 2019). The estimated 12 million tonnes of grain lost annually, equates to 9.6 TWh of energy for production, and a GHG cost of 13 MtCO2e.

This would be the case if addressing losses lead to a corresponding reduction in net production, and hence, resource inputs. This study looks at a different case, whereby the benefits from tackling grain losses accrue on the demand side, i.e. additional nutrient supply.

In an absolute sense, diverting the nutrients from lost grain to additional supply could provide $93 \pm 8 \times 10^9$ kCal of calories, $25 \pm 2 \times 10^8$ g of protein, $69 \pm 6 \times 10^7$ mg of iron, $56 \pm 5 \times 10^7$ mg of zinc, and $25 \pm 2 \times 10^8$ mcg of vitamin A per day. More informatively, when applying RDA's of these nutrients for India (using one Consumption Unit as a typical consumer), we find that around 40 million people could have their daily calorie, protein, iron and zinc needs met. Additional supply of Vitamin A is much less substantial, covering the needs of 4 million people.

Moving beyond absolute estimates of additional nutrients, we now look to quantify the relative impact on nutrient deficiency within Indian populations. Figure 4 compares the contribution each type of grain could make, if losses were eliminated and supply increased, to reducing the average gap in intake for those with some kind of nutrient deficiency. It shows that, at a national level, eliminating losses from the five major grains studied could have a large impact on average deficiencies of some key nutrients.

The largest improvement comes by way of protein intake, with the potential to deliver 46% of total deficiency should losses be eliminated and grain supply increased. In absolute terms, this aggregated potential is equal to around 2.5 kt of protein per day, against an estimated total protein deficiency of around 5.5 kt per day. This appears to be a significant proportion, but must be viewed in the wider context and the deficiency estimate caveats previously detailed. Cereals constitute the largest source, around 57%, of protein in Indian diets (Minocha et al., 2017). Moreover, protein deficiency in India, although a problem, is less prevalent than other nutrients. This is shown by Harinarayan et al. (2019), who present data from India's National Nutrition Monitoring Bureau (NNMB, 2017, 2012) that puts average household protein intake at ~90% of RDA in urban areas and ~82% of RDA in rural areas. This is in comparison to less than 80% of RDA for calories, and ~50% for both iron and vitamin A of average rural household intake.


a) Additional nutrient supply per capita

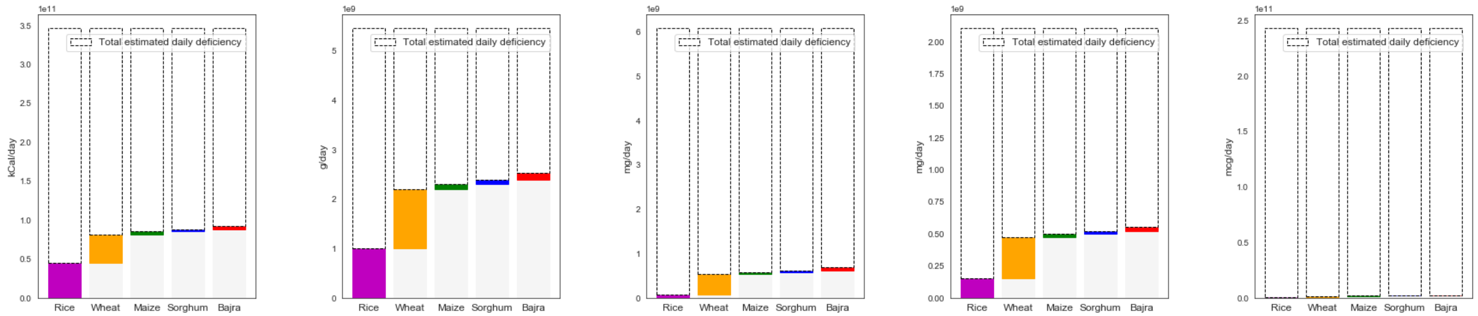

b) Total additional nutrient supply

Figure 4: The potential contribution of eliminating food losses of major grains (rice, wheat, maize, sorghum, bajra) in improving average nutrient intake among India's nutrient deficient population. The y-axis shows nutrient consumption per day, on a per person basis for the top panel (a), and on an absolute measure for the bottom panel (b). Note the exponent and its value that accompany the y-axis units on the bottom panel. Red lines give estimated current average daily intake for those with some kind of deficiency, black lines give the RDA for one Consumption Unit in India, pink lines are a summation of the individual contributions from each grain, giving a potential improved average daily intake from increased supply.

Calories and zinc, and to a lesser degree iron, also showed sizeable improvement, with the potential to supply, should grain losses be eliminated, 27%, 26% and 11% of total deficiency respectively. Vitamin A deficiency showed negligible potential for improvement. Eliminating grain losses across the supply chain would only reduce deficiency in this nutrient by ~1%. The result is largely explained by India having the highest prevalence of vitamin A deficiency in South Asia (Akhtar et al., 2013), and the low amounts contained in rice and wheat.

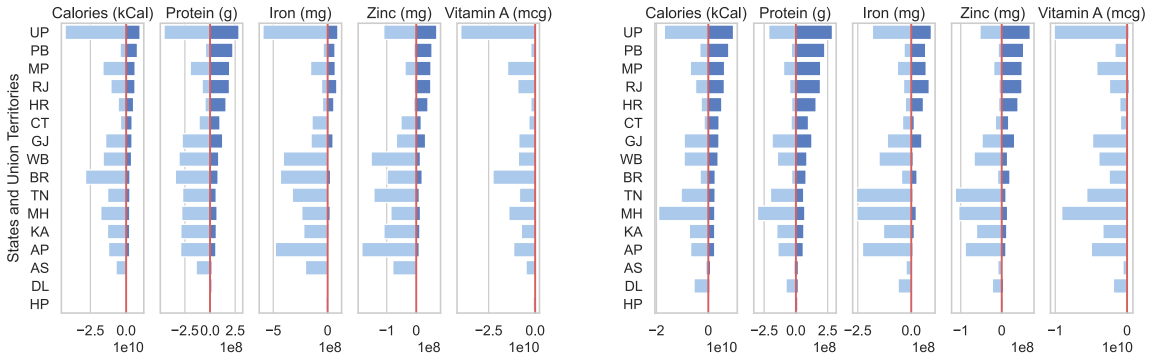
Within grains, rice and wheat dominate recovered nutrition from supply chain losses. This is due to their overwhelming share of grain production for human consumption, ~88Mt each, compared with ~24Mt for maize, bajra and sorghum combined. However, different nutritional profiles and loss rates of grains do have an impact. This can be seen in the relative larger contribution of wheat to rice in improving protein, iron and zinc, despite very similar consumption. In particular, rice and wheat account for 40% and 47% of the additional protein supply, but 12% and 67% of iron. Indeed, iron contained within potential increased bajra supply has an equal contribution (~12%) to that of rice, owing to its comparatively rich nutrient profile, despite radically less production.

Between 60%-70% of grain production is retained by farmers, with the remainder marketed (Sharon et al., 2014). It is not generally known how much of marketed production is consumed within states. Here we assume that all of marketed production does indeed remain in state along with that retained by farmers. We explore heterogeneity (both spatially and between urban/rural populations) of potential reductions in nutrient deficiency by eliminating grain losses during supply.

Figure 5 shows how deficiency varies across India's 35 states and territories for urban (Figure 5a and Figure 5b) and rural populations (Figure 5c and Figure 5d). For comparison, we assume all potential nutrient benefit from increased supply is diverted to either urban or rural populations. Note, the top two panels of Figure 5 have units in the range $10^8 – 10^{10}$, the lower two panels, with units in the range $10^7 – 10^9$, are separated to make these results visible. Intrastate distribution (i.e. net importers or exporters) of rice and wheat is not accounted for, as it is problematic to attribute these losses to specific states, and the nutrients they could supply to their local population. For context, this means that 66% of rice and 78% of wheat is accounted for, along with 100% of maize, bajra and sorghum for human consumption. The latter three grains are unaffected here as they tend to be far more limited in their distribution. There is a significant state imbalance in the potential to address nutrient deficiency from eliminating grain losses. Uttar Pradesh (UP) has the largest potential increased supply of calories, protein, iron, and zinc should grain losses from its domestic production by eliminated. However, it also has comparatively large nutrient deficiency. Across urban and rural populations, Punjab (PB), Madhya Pradesh (MP), Rajasthan (RJ) and Haryana (HR) are states that, if losses were eliminated, could deliver the largest proportional benefit in addressing nutrient deficiency. This extra supply could deliver around four times the respective protein deficiency in each of these states.

a) Biggest nutrient supply increase vs urban pop. deficiency

c) Biggest nutrient supply increase vs rural pop. deficiency



b) Smallest nutrient supply increase vs urban pop. deficiency

d) Smallest nutrient supply increase vs rural pop. deficiency

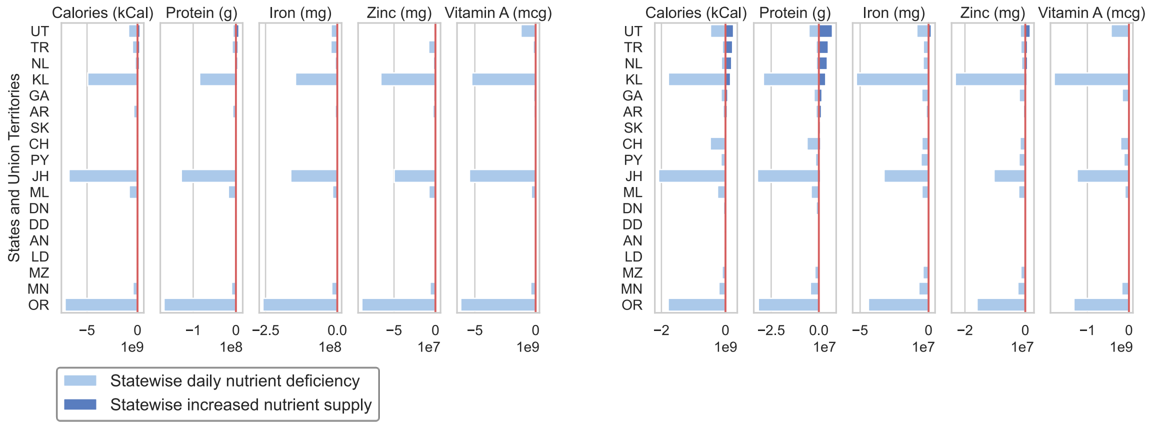


Figure 5: Sub-national distribution of current deficiency and potential improved supply of five nutrients across Indian. Y-axes show states and union territories and x-axes show the magnitude per day of each nutrient. Estimated total daily deficiency for each area is given by light blue bars, and the increased nutrient supply in eliminating losses is given by dark blue bars. Figure 5a and Figure 5b give this for urban populations, Figure 5c and Figure 5d for rural populations. Top and bottom panels are separated to allow visual inspection of small potential supply increases in eliminating losses. State and union territory codes are given in Table A.3 of the Appendix.

This contrasts with urban populations in Kerala (KL), Jharkhand (JH) and Odisha (OR), which have comparatively large nutrient deficiency versus negligible potential for increased nutrient supply. As shown in Figure 4, and now clear at a sub-national level from Figure 5, substantial vitamin A deficiency particularly among urban populations, cannot be addressed by eliminating grain losses and diverting the increased nutrient supply from grains. Any measures to reduce food grain losses should be aware of local context but also look to maximise inter-state opportunities.

4 Conclusion

Cereal grains constitute a major part of Indian diets, but around 10Mt are lost in supply chains each year that could have otherwise been consumed. Unaddressed, population led demand could see this increase to 11.2-11.8 Mt by 2030 under future SSP scenarios. The fact that India's grain losses are, on a per cent basis, comparatively low may raise questions of whether they should receive any particular policy interest. Aside from the sheer magnitude of grain production and consumption, we have shown that addressing these losses could reduce key nutrient deficiencies and quantified, for the first time, the role of energy in one part of the grain supply chain.

Modern silo infrastructure can minimise grain losses in the storage component of supply chains, however, this requires energy input to create and maintain favorable ambient conditions. We find that energy to provide suitable storage conditions is in the range 72 to 110 kWh per tonne of grain, and is largely dependent on the harvest and storage moisture content and intrinsic biophysical properties. This corresponds to a relatively small proportion – 8% to 16% – of the energy input to produce the grain, but represents a clear trade-off and should be considered alongside the benefits of additional supply from minimising grain losses in storage. Reducing food grain losses contributes to achieving SDG12.3, but also has synergy with health and diet targets under SDG2. We explore the interaction between eliminating supply chain grain losses and the resulting increased supply of five key nutrients in India. We estimate that across rice, wheat, maize, bajra and sorghum, increased daily supply from eliminated losses could provide 93×10^9 kCal of calories, 2.5×10^9 g of protein, 6.9×10^8 mg of iron, 5.6×10^8 mg of zinc and 2.5×10^9 mcg of vitamin A. Accepting caveats, we estimate that for deficient populations, this equates to addressing 27%, 46%, 11%, 26%, and 1% respectively of average daily deficiency.

The contribution to the scientific community is twofold. One, we have presented a method to analyse energy requirements for effective grain storage, that is generalisable to other countries and regions and applicable to multiple grain types. Second, we have applied this method to derive empirical insight on India as a case study and couple this with an assessment of the nutrients associated with grain loss, and in do so contextualising the quantification of losses in tangible human terms.

Generally, there is a need for more systematic and empirical data on losses to support analysis and policy formation on food systems in India and globally. From a policy perspective, this study gives evidence for an adaptive solution to the significant issue of food loss and food security in India. It provides policy makers with a quantified assessment, with appropriate uncertainty, for the storage energy demands of India's predominant food grains. This is a valuable adjunct, and arguably necessary preliminary analysis, to the roll out and scale up of India's modernised silo programme. Specifically, it supports prioritisation of energy resources in any constrained geographies and provides baseline empirical modelling to feed into a more detailed whole system engineering assessment of grain supply chain, storage and losses.

4.1 Limitations

A limitation of the nutrient deficiency analysis, previously identified in Rao et al. (2018), is that the RDA for India reflects a typical diet, which masks expected heterogeneity in different population groups' nutritional needs. Moreover, we use a single representative value for each nutrient of each grain. In reality, people consume different varieties of grain species (e.g. brown vs white rice) which have different nutrient profiles. Moreover, we do not consider how these nutrient profiles may change under climate change. Another element that is not considered, due to its complexity, is the bio-availability of nutrients. This refers to the proportion of nutrients that are actually absorbed and utilised by a person and is dependent on a number of food-related and physiological factors. Data from the food loss survey were only collected over a one year period and, although in line with other assessments (Nanda et al., 2012), confidence in loss rates would increase with multi-year observation. Finally, we assume that all nutrients can be recovered from all grain losses along the supply chain. In practice this will not be the case, and so this analysis should be seen as an upper limit that can help guide policy discussion.

4.2 Opportunities for future research

Different food groups have different loss rates, total production, and nutritional profiles, which should be examined to understand the potential magnitude of recovered nutrition. This is important, as Indian diets are expected to shift over the coming decades due to urbanisation, per capita income and preference changes, to greater consumption of fruit, vegetables and dairy (Alae-Carew et al., 2019). Moreover, many food items in these groups are perishable and so require more energy input through the supply chain to minimise losses. Future research could extend this work by assessing the full lifecycle energy inputs from production through supply chains to consumers, and the energy 'investment' required to minimize the losses through this system e.g. in farm operations and transport.

Should data become available, future studies should investigate the flows of food grain supply through India. The spatial distribution of loss could then be examined to understand the potential increase in nutritional supply with regards to local population and their dietary habits, preferences and needs. In terms of projecting losses, research should look at how sub-national differences in loss rates may change or diverge under future development scenarios. Behavioral aspects of diet present a major challenge and more research should be undertaken to help bound and inform the feasibility and robustness of studies such as this. Beyond India, future work should extend to countries in East and South Asia, and Sub-Saharan Africa – regions with high levels of food loss.

5 References

Akhtar, S., Ahmed, A., Randhawa, M.A., Atukorala, S., Arlappa, N., Ismail, T., Ali, Z., 2013. Prevalence of vitamin A deficiency in South Asia: causes, outcomes, and possible remedies. J. Health. Popul. Nutr. https://doi.org/10.3329/jhpn.v31i4.19975

Alae-Carew, C., Bird, F.A., Choudhury, S., Harris, F., Aleksandrowicz, L., Milner, J., Joy, E.J., Agrawal, S., Dangour, A.D., Green, R., 2019. Future diets in India: A systematic review of food consumption projection studies. Glob. Food Sec. https://doi.org/10.1016/j.gfs.2019.05.006

Arku, A.Y., Aviara, N.A., Ahamefula, S.C., 2012. Specific Heat of Selected Legumes and Cereal Grains Grown in North Eastern Nigeria. Arid Zo. J. Eng. Technol. Environ. 8, 105–114.

Bhutia, D., 2014. Protein energy malnutrition in India: The plight of our under five children. J. Fam. Med. Prim. Care 3, 63. https://doi.org/10.4103/2249-4863.130279

Cao, Y., Li, G., Zhang, Z., Chen, L., Li, Y., Zhang, T., 2010. The specific heat of wheat. https://doi.org/10.5073/jka.2010.425.202

Cenkowski, S., Jayas, D.S., Hao, D., 1992. Latent heat of vaporization for selected foods and crops. Can. Agric. Eng. 34, 281–286.

Chapke, R., Prabhakar, Shyamprasad, G., Das, I., Tonapi, V., 2018. Improved millets production technologies and their impact.

Conrad, Z., Niles, M.T., Neher, D.A., Roy, E.D., Tichenor, N.E., Jahns, L., 2018. Relationship between food waste, diet quality, and environmental sustainability. PLoS One 13. https://doi.org/10.1371/journal.pone.0195405

Davis, K.F., Chhatre, A., Rao, N.D., Singh, D., Ghosh-Jerath, S., Mridul, A., Poblete-Cazenave, M., Pradhan, N., DeFries, R., 2019. Assessing the sustainability of post-Green Revolution cereals in India. Proc. Natl. Acad. Sci. U. S. A. https://doi.org/10.1073/pnas.1910935116

Defries, R., Chhatre, A., Davis, K.F., Dutta, A., Fanzo, J., Ghosh-Jerath, S., Myers, S., Rao, N.D., Smith, M.R., 2018. Impact of Historical Changes in Coarse Cereals Consumption in India on Micronutrient Intake and Anemia Prevalence. Food Nutr. Bull. 39, 377–392. https://doi.org/10.1177/0379572118783492

Directorate of Economics & Statistics, n.d. Crop Production Statistics Information System [WWW Document]. URL https://aps.dac.gov.in/APY/Index.htm (accessed 12.23.19).

Directorate of Marketing & Inspection, 2005. Agriculture Marketing [WWW Document]. Minist. Agric. Farmers Welfare, Gov. India. URL http://www.agmarknet.gov.in/ (accessed 11.9.19).

Directorate of Millets Development, 2017. Pearl millet [WWW Document]. URL http://millets.dacfw.nic.in/POP Pearl.html (accessed 11.9.19).

FAO, 2019. The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction. Rome.

FAO, 2018. Methodological Proposal for Monitoring SDG Target 12.3: The Global Food Loss Index Design, Data Collection Methods and Challenges.

FAO, 2016. How access to energy can influence food losses.

FAO, 1994. Agricultural engineering in development - The harvest [WWW Document]. URL http://www.fao.org/3/T0522E/T0522E05.htm#Physiological maturity (accessed 11.9.19).

Graintechnik, 2019. GT-450 | Graintechnik Pvt. Ltd [WWW Document]. URL http://graintechnik.com/products/units/gt-450.php (accessed 11.12.19).

Graintechnik, 2018. Long Term Storage Of Grains With Grain Chilling Technology [WWW Document]. URL https://www.iaom.info/wp-content/uploads/06graintechnik18sar.pdf (accessed 11.9.19).

Harinarayan, C.V., Akhila, H., 2019. Modern India and the Tale of Twin Nutrient Deficiency–Calcium and Vitamin D–Nutrition Trend Data 50 Years-Retrospect, Introspect, and Prospect. Front. Endocrinol. (Lausanne). 10. https://doi.org/10.3389/fendo.2019.00493

Heard, B.R., Miller, S.A., 2019. Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System. Environ. Sci. Technol. 53, 251–260. https://doi.org/10.1021/acs.est.8b05322

Heard, B.R., Miller, S.A., 2016. Critical Research Needed to Examine the Environmental Impacts of Expanded Refrigeration on the Food System. Environ. Sci. Technol. 50, 12060–12071. https://doi.org/10.1021/acs.est.6b02740

HGCA, 2011. Grain storage guide for cereals and oilseeds [WWW Document]. URL https://ahdb.org.uk/grainstorage (accessed 1.22.20).

Iguaz, A., San Martín, M.B., Arroqui, C., Ferníndez, T., Matí, J.I., Vírseda, P., 2003. Thermophysical properties of medium grain rough rice (LIDO cultivar) at medium and low temperatures. Eur. Food Res. Technol. 217, 224–229. https://doi.org/10.1007/s00217-003-0760-x

Indian Council of Medical Research, 2009. Nutrient Requirements and Recommended Dietary Allowances for Indians.

IPCC, 2019. Special Report on Climate Change and Land - Chapter 5: Food Security.

IRRI, 2019. Measuring moisture content - IRRI Rice Knowledge Bank [WWW Document]. URL http://www.knowledgebank.irri.org/step-by-step-production/postharvest/milling/milling-and-quality/measuring-moisture-content-in-milling (accessed 11.11.19).

Jha, S.N., Vishwakarma, R.K., Ahmad, T., Dixit, A.K., 2015. Assessment of Quantitative Harvest and Post-Harvest Losses of Major Crops/Commodities in India. ICAR-CIPHET.

Kumar, D., Kalita, P., 2017. Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries. Foods 6, 8. https://doi.org/10.3390/foods6010008

Lindgren, E., Harris, F., Dangour, A.D., Gasparatos, A., Hiramatsu, M., Javadi, F., Loken, B., Murakami, T., Scheelbeek, P., Haines, A., 2018. Sustainable food systems—a health perspective. Sustain. Sci. 13, 1505–1517. https://doi.org/10.1007/s11625-018-0586-x

Love, D.C., Fry, J.P., Milli, M.C., Neff, R.A., 2015. Wasted seafood in the United States: Quantifying loss from production to consumption and moving toward solutions. Glob. Environ. Chang. 35, 116–124. https://doi.org/10.1016/j.gloenvcha.2015.08.013

Lutz, W., Goujon, A., Samir, K.C., Stonawski, M., Stilianakis, N., 2018. Demographic and human capital scenarios for the 21st century 2018 assessment for 201 countries. https://doi.org/10.2760/835878

Lynch, S.R., 2011. Why Nutritional Iron Deficiency Persists as a Worldwide Problem. J. Nutr. 141, 763S-768S. https://doi.org/10.3945/jn.110.130609

Manandhar, A., Milindi, P., Shah, A., 2018. An Overview of the Post-Harvest Grain Storage Practices of Smallholder Farmers in Developing Countries. Agriculture 8, 57. https://doi.org/10.3390/agriculture8040057

Minocha, S., Thomas, T., Kurpad, A. V, 2017. Dietary Protein and the Health–Nutrition–Agriculture Connection in India. J. Nutr. 147, 1243–1250. https://doi.org/10.3945/jn.116.243980

Müller, O., Krawinkel, M., 2005. Malnutrition and health in developing countries. CMAJ. https://doi.org/10.1503/cmaj.050342

Muthayya, S., Rah, J.H., Sugimoto, J.D., Roos, F.F., Kraemer, K., Black, R.E., 2013. The Global Hidden Hunger Indices and Maps: An Advocacy Tool for Action. PLoS One 8, e67860. https://doi.org/10.1371/journal.pone.0067860

Nanda, S., Vishwakarma, R., Bathla, H., Rai, A., Chandra, P., 2012. Harvest and Post Harvest Losses of Major Crops and LIvestock Produce in India.

Neff, R.A., Kanter, R., Vandevijvere, S., 2015. Reducing food loss and waste while improving the public's health. Health Aff. 34, 1821–1829. https://doi.org/10.1377/hlthaff.2015.0647

NNMB, 2017. National Nutrition Monitoring Bureau Technical Report No. 27 [WWW Document]. Indian Counc. Med. Res. URL http://ninindia.org/NNMB Urban Nutrition survey report-Final 25-09-2017.pdf (accessed 12.2.19).

NNMB, 2012. National Nutrition Monitoring Bureau Technical Report No. 26 [WWW Document]. Indian Counc. Med. Res. URL http://www.nnmbindia.org/1_NNMB_Third_Repeat_Rural_Survey___Technicl_Report_26.pdf (accessed 12.2.19).

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Rao, N.D., Min, J., DeFries, R., Ghosh-Jerath, S., Valin, H., Fanzo, J., 2018. Healthy, affordable and climate-friendly diets in India. Glob. Environ. Chang. 49, 154–165. https://doi.org/10.1016/j.gloenvcha.2018.02.013

Rao, N.D., Poblete-Cazenave, M., Bhalerao, R., Davis, K.F., Parkinson, S., 2019. Spatial analysis of energy use and GHG emissions from cereal production in India. Sci. Total Environ. 654, 841–849. https://doi.org/10.1016/j.scitotenv.2018.11.073

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Chang. 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Ritchie, H., Reay, D., Higgins, P., 2018. Sustainable food security in India—Domestic production and macronutrient availability. PLoS One 13. https://doi.org/10.1371/journal.pone.0193766

Roohani, N., Hurrell, R., Kelishadi, R., Schulin, R., 2013. Zinc and its importance for human health: An integrative review. J. Res. Med. Sci. 18, 144–157.

Sawant, A.A., Patil, S.C., Kalse, S.B., Thakor, N.J., 2012. Effect of temperature, relative humidity and moisture content on germination percentage of wheat stored in different storage structures. Agric. Eng. Int. CIGR J. 14, 110–118.

Sharon, M.M.E., Abirami, C.V.K., Alagusundaram, K., 2014. Grain storage management in India. J. Postharvest Technol. 2.

Singh, K.P., Mishra, H.N., Saha, S., 2011. Sorption Isotherms of Barnyard Millet Grain and Kernel. Food Bioprocess Technol. 4, 788–796. https://doi.org/10.1007/s11947-009-0195-x

Spiker, M.L., Hiza, H.A.B., Siddiqi, S.M., Neff, R.A., 2017. Wasted Food, Wasted Nutrients: Nutrient Loss from Wasted Food in the United States and Comparison to Gaps in Dietary Intake. J. Acad. Nutr. Diet. 117, 1031-1040.e22. https://doi.org/10.1016/j.jand.2017.03.015

USDA, 2019. India: Grain and Feed Annual [WWW Document]. URL https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Grain and Feed Annual_New Delhi_India_3-29-2019.pdf (accessed 9.26.19).

Wu, Y., Benjamin, E.J., MacMahon, S., 2016. Prevention and control of cardiovascular disease in the rapidly changing economy of China. Circulation 133, 2545–2560. https://doi.org/10.1161/CIRCULATIONAHA.115.008728

Xue, L., Liu, G., Parfitt, J., Liu, X., Van Herpen, E., Stenmarck, Å., O'Connor, C., Östergren, K., Cheng, S., 2017. Missing Food, Missing Data? A Critical Review of Global Food Losses and Food Waste Data. Environ. Sci. Technol. 51, 6618–6633. https://doi.org/10.1021/acs.est.7b00401

6 Appendix

Parameter	Upper	Lower
Rice	FAO's Agricultural engineering in development, section on physiological maturity at harvest (FAO, 1994)	Sourced from India's Directorate of Marketing and Inspection profile on rice (Directorate of Marketing & Inspection, 2005), and the International Rice Research Institute's (IRRI) rice knowledge bank (IRRI, 2019)
Wheat	20% given in agricultural marketing grain profiles of India's DMI (2005). Authors assign upper value at 20% + 2%, i.e. 22%.	20% given in agricultural marketing grain profiles of India's DMI (2005). Authors assign upper value at 20% - 2%, i.e. 18%.
Maize	Sourced from India's Directorate of Marketing and Inspection profile on maize. (Directorate of Marketing & Inspection, 2005)	FAO's Agricultural engineering in development, section on physiological maturity at harvest (FAO, 1994)
Sorghum	FAO's Agricultural engineering in development, section on physiological maturity at harvest (FAO, 1994)	FAO's Agricultural engineering in development, section on physiological maturity at harvest (FAO, 1994)
Bajra	Moisture content of 20% given by India's Directorate of Millet Development. Authors assign upper value at 20% + 2%, i.e. 22%. (Directorate of Millets Development, 2017).	Moisture content of 20% given by India's Directorate of Millet Development. Authors assign upper value at 20% - 2%, i.e. 18%. (Directorate of Millets Development, 2017)

Table A.1: Sources for moisture content at harvest for each of the five grains studied.

Parameter	Upper	Lower	Description and source
Specific heat capacity ($kJkg^{-1}K^{-1}$)	3.5	1	Specific heat capacity is a function of moisture content and to a lesser degree temperature. However, due to lack of available data, here, unlike for specific heat enthalpy, which is modelled explicitly, we take literature values of grain specific heats to parameterise the energy model. See Arku et al., 2012; Cao et al., 2010; Iguaz et al., 2003.

Storage duration (months)	12	3	Values parametrised using industry literature of grain chiller manufacturer for the Indian market (Graintechnik, 2019, 2018). Upper and lower determined by authors.
No. 'ON' days per month	8	1	
No. run hours per 'ON' day	24	12	
Coefficient of Performance (COP)	3	2	
Average power rating (kW)	85.8	70.2	
Field temperature (°C)	35	25	

Table A.2: Parameters and sources of values for the energy model of grain storage.

State/Union Territory	**Code**	**State/Union Territory**	**Code**
Andaman and Nicobar Islands	AN	Lakshadweep	LD
Andhra Pradesh	AP	Madhya Pradesh	MP
Arunachal Pradesh	AR	Maharashtra	MH
Assam	AS	Manipur	MN
Bihar	BR	Meghalaya	ML
Chandigarh	CH	Mizoram	MZ
Chhattisgarh	CT	Nagaland	NL
Dadra and Nagar Haveli	DN	Odisha	OR
Daman and Diu	DD	Puducherry	PY
Delhi	DL	Punjab	PB
Goa	GA	Rajasthan	RJ
Gujarat	GJ	Sikkim	SK
Haryana	HR	Tamil Nadu	TN
Himachal Pradesh	HP	Telangana*	TG
Jammu and Kashmir	JK	Tripura	TR
Jharkhand	JH	Uttar Pradesh	UP
Karnataka	KA	Uttarakhand	UT
Kerala	KL	West Bengal	WB

*Nutrition data precedes formation of Telangana state. Districts within this state are captured in Andhra Pradesh.

Table A.3: Two-letter codes for Indian states and union territories.

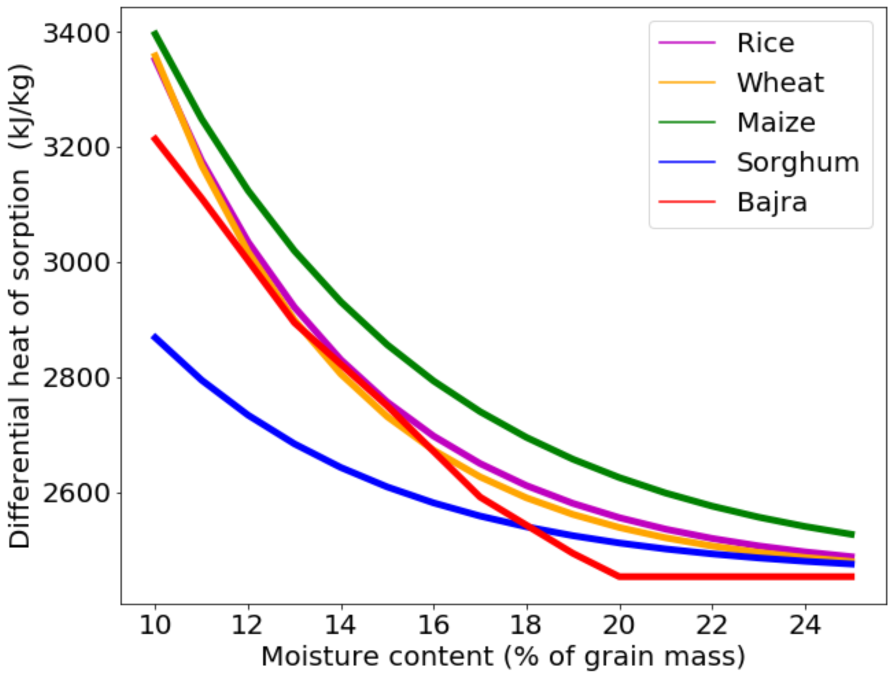


Figure A.1: Curves showing the relationship between differential heat of sorption and moisture content curves for the five grains studied. Rice, wheat, maize, and sorghum curves are sourced from Cenkowski et al. (1992), the bajra curve is from Singh et al. (2011).

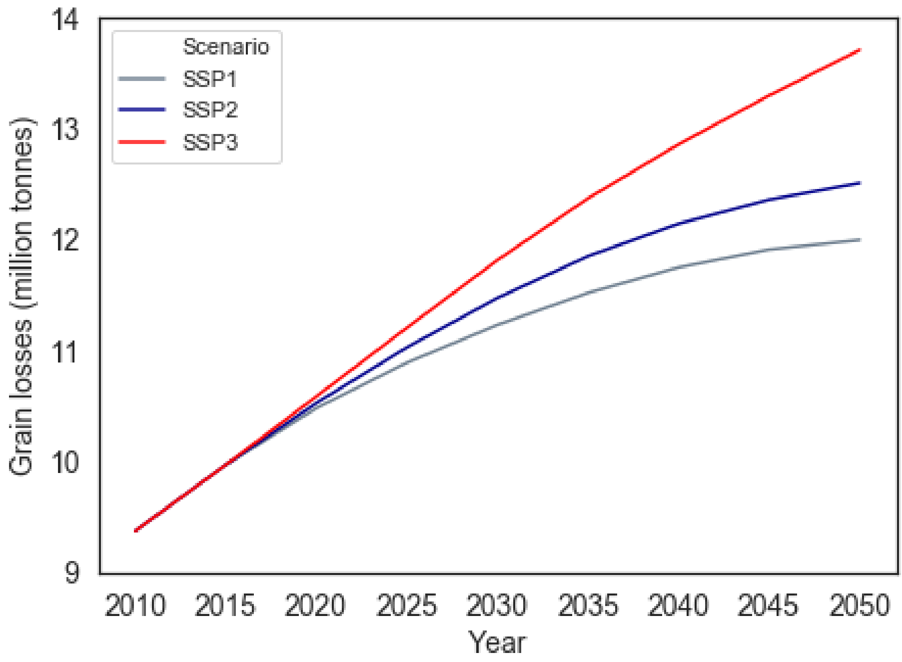


Figure A.2: Scenarios for losses from grain intended for human consumption in India out to 2050, based on population projections from three Shared Socioeconomic Pathways (SSPs). Population data from Wittgenstein Centre for Demography and Global Human Capital (Lutz et al., 2018). Wittgenstein Centre Data Explorer Version 2.0.