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ASSESSING GLOBAL WATER AND FOOD CHALLENGES: TIME TO RETHINK ON METHODS?

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Assessing Global Water and Food Challenges: Time to Rethink on Methods?

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Summary

The paper analyses the food security and water management challenges facing the world, at the level of individual nations, but does so by delinking the food security challenges from those of supplying water to meet the needs of industries, livestock, domestic sectors and environmental sectors. The paper is based on the premise that assessing the food security scenario purely from a water resource perspective gives a distorted view of the food security challenges facing a country. Similarly, assessing the water management challenges purely from the point of view of renewable water resource availability also can be misleading.

The fact that land would become a major constraint to food production in many water rich as well as water scarce countries, and the comparative advantages some water scarce countries enjoy in producing surplus for trade by virtue of their access to large amount of agricultural land makes it imperative to have separate criteria for assessing water self-sufficiency, magnitude of future water scarcity and food security challenges facing a country.

Using global data sets, the paper first examines how the positioning of a country vis-à-vis per capita renewable water availability and per capita arable land determines the extent of water utilization for various uses and the extent to which arable land is put to crop cultivation, respectively. It then tries to simulate the complex interaction between arable land availability (and cultivated land and pasture land) and renewable water resources that decides the agricultural production potential and dairy production capability of a country.

The paper also critically examines the validity of the arguments made for countries to reduce their agricultural water footprints on the basis of data on their irrigation water withdrawals and water footprint in their diet, by taking into account the two important facts: 1] water in the soil profile is a major component

of total agricultural water withdrawal for many countries; and 2] many countries maintaining diets with high water content actually import large amounts of food.

A composite water-land index, which evaluates the adequacy of water resources to bring the entire cultivated land under irrigated production (water adequacy index, whose maximum value is taken as 1.0), and the amount of cultivated land per capita (ha), was derived to simulate the agricultural production potential of different countries. The robustness of this index was tested by using it as an independent variable in a statistical model that uses per capita virtual water trade as dependent variable. A composite index, which adds up the value of water-land index and the pasture land index (=pasture land per capita X pasture land coefficient) was also derived to simulate the milk production capability of different countries. It was used as an independent variable in a statistical model that uses per capita milk production as dependent variable.

The analyses show that per capita agricultural land availability is an important factor that determines what proportion of the agricultural land would be used by countries for cultivation and how much would be left as permanent pastures, if water is not a constraint. The analyses also show that certain countries are able to leave a large proportion of the 'blue water in their territory into the hydrological system for ecology, because they have large amount of renewable water resources, disproportionately higher than the cultivated land. This means the countries having limited amount of renewable water resources, but considerably large amount of arable land would find it extremely difficult to leave water for the environment.

Further, our analysis shows that irrigation water withdrawal is a small fraction of total water withdrawals for agriculture; many countries which leave high water footprint in their diet draw very little water for agriculture; many countries, which leave high water footprint in agriculture, have their people maintaining diets with low water footprint and exporting the surplus; and there are very few countries which have high water footprint in agriculture and their diet and remain water-scarce. Therefore, the norms of using estimates of 'water footprint in human diet' and 'irrigation water withdrawals' as the basis for assessing the magnitude of problems associated with high water footprint in agriculture can be highly misleading in terms of determining which countries to target.

The 'water-land index' computed for 152 countries explained the per capita virtual water export from and import into these countries to the extent of

55 percent. The composite index reflecting the adequacy of water for intensifying irrigated cultivation, amount of cultivated land and pasture land availability explained the level of per capita milk production in these countries to the extent of 64 per cent. When the value of the index increased, milk production per capita increased.

Thus the criteria for assessing the magnitude of food security and water management challenges have to change to factor in the role of agricultural land, particularly the cultivated land. When this is done we have four different categories of countries emerging: 1] countries with large amount of renewable water and cultivated land, which have both water and food self-sufficiency; 2] countries having large amount of renewable water resources but also having disproportionately larger amount of cultivated land, resulting in low 'water-adequacy' but 'food-surplus' situation, though with occasional water scarcity; 3] countries having sufficient amount of cultivated land, but low water availability, facing different degrees of water shortages (with some experiencing groundwater mining problems) and food insufficiency, depending on the actual per capita cultivated land, water availability and extent of its utilization for irrigation; and, 4] countries having high values of 'water adequacy' mostly because of large amount of renewable water and low per capita cultivated land and sometimes because of disproportionately lower amount of cultivated land even with low water availability, but mostly dependent on food imports.

There are around 60 countries belonging to the fourth category, which have adequate amount of water in the natural system that can be tapped to increase cropping intensity, thereby reducing the extent of food imports. On the other hand, there are 20 water scarce countries belonging to the third category with poor water adequacy for crop production, which also have some amount of water still remaining un-utilized that can be harnessed to increase irrigation.

1 Introduction

Water is needed for growing food, feed and fodder; water is needed for human and animal consumption; manufacturing processes; power generation; and finally water is needed by the environment. Globally, food, fodder and feed production consumes the largest amount of water today and would continue to be so for many decades to come. One major factor of production in agriculture is availability of land (Yao and Liu, 1998; Helfand and Levine, 2004; Kumar and Singh, 2005). Yet, the challenges of growing food, feed and fodder and meeting water needs of domestic, urban, industrial and environmental sectors are all generally bundled under water management challenges, perhaps because of the crucial role water plays in the day to day life of humans as a life-saving and life threatening resource. As a result, the global, national and regional challenges in meeting future water and food supplies are viewed from the perspective of managing water.

Global water scarcity maps are generated by scientific institutions on the basis of estimation of water demand for all the above mentioned sectors in different regions and comparing them against renewable water supplies in the respective regions. Such maps are used to arrive at inferences about the nature of water scarcity--whether physical, or economic (Seckler at al., 1998), and the degree of scarcity, whether absolute water scarcity or water scarce or water stressed (Falkenmark, 1989). Such inferences are used to draw conclusions on whether a region or country would face shortage of water for food production or economic growth or even basic survival needs. This is a highly water-centric approach. The best example is the widely used physical water scarcity index, which is used to indicate the sufficiency of water for economic production functions including agricultural production and basic survival needs in a region, merely looking at the renewable water resources per capita without considering how much land is available for agricultural production. Obviously, an area which has very large amount of cultivated land per capita would require much more water than one which has very small per capita cultivated area, though both have the same size of population and agricultural production, especially food requirements.

Such an approach, which has been followed for several decades, had led to a skewed understanding of the nature of challenges we would face in future concerning water and food. For instance, estimates of (utilizable) renewable water resources exceeding aggregate demand for water for any given region led to the highly erroneous conclusion that there would be sufficient water to meet all needs there, and that there would be no major problem in producing food for the future population, and meeting all their water supply needs. Conversely, estimates of renewable water supplies below the aggregate demand of water for meeting various needs for any given region eventually led to the conclusion that the region would face water scarcity problems (Seckler *et al.*, 1999; Postel, 2000; Rijsberman, 2006). Such figures are transposed with population projection figures to predict future water scarcity and such projections have become the basis for 'doomsday prophecies'.

As noted by Kumar and Singh (2005), assessing the food security challenge facing a country purely from a water resources perspective provide a distorted view of the food security scenario of that country. It may bring in complacency for water-rich nations that they could be food-secure; and unwanted pessimism for water scarce nations that they won't have sufficient water to produce food. The point is that access to arable land is equally or even more important for food security and therefore should be integrated with other considerations in formulating national food and water policies. In the same manner, assessing the water management challenges faced by nations purely from the point of view of renewable water availability and aggregate demands will be dangerous. Access to water in the soil profile would be an important determinant of effective water availability for food production, from which a major portion of the aggregate demand for water comes (see for instance Kumar and Singh, 2005; Molden *et al.*, 2007; Hanjra and Qureshi, 2010; Kumar, 2010; Mekonnen and Hoekstra, 2011). Conversely, large size of cultivated land in per capita terms increases the demand for water in the agriculture sector and can induce water scarcity situation, even with moderately high renewable water resources per capita.

The problems, however, do not end there. Such methodological flaws also lead to erroneous conclusions about the magnitude of water scarcity and food insecurity problems in different countries and regions within countries. Often future food demand is translated into equivalent water demand, and the same is compared against the utilizable water supplies. Consequently, suggestions are made to increase the utilization of the available water and improve the overall access to water (see for instance Rosegrant *et al.*, 2009, Namara *et al.*, 2010; Mukherji *et al.*, 2012), completely ignoring the critical question, i.e., whether sufficient land to produce food using this water is available or not. Obviously, for land scarce regions, such solutions would be seriously flawed. Ideally, what need to be assessed are: the maximum amount of water that the available arable land in the region in question can absorb for irrigation under the highest possible intensity of land use for crop production; the maximum production possible under the scenario of most intense land use; and the amount of food that has to be imported (given the likely future deficit) from other regions that have surplus land.

This new paradigm in analyzing food and water challenges, which integrates arable land as a key variable from both supply and demand side of the water equation and supply side of the food equation, would force us to reconsider the estimates of future food production requirements for regions or countries that have excess amount of arable land. Obviously, in addition to meeting own demand, such regions and countries also will have to produce surplus for export to regions that are land scarce. Hence, the estimation of future water demand for agriculture in such regions cannot be merely based on the amount of food people in those regions would require in future, and instead should include the quantum of surplus food for export to the neighbouring food insecure regions or countries that are the potential buyers of these agricultural commodities, even if the former are water-scarce. The simple reason is the rising demand for food in the international market would force countries which have the production potential to produce surplus and export. This is quite contrary to the conventional wisdom of suggesting food import by such regions to reduce their water footprint (Allan, 1997; Hoekstra, 2003) which does not take cognizance of the fact that water rich regions often lack sufficient arable land to produce even to meet their own needs due to high population density.

Such a paradigm would add a new dimension to the global debate on food and water policy for countries and regions by bringing out very clearly the type of inter-dependence that currently exists or is likely to develop in future between countries and regions within countries for achieving water and food security, in the form of inter-country and inter-regional water transfer and inter-country and inter-regional food trade.

In this paper we attempt the following: 1] assessing the nature of challenges facing different countries, i.e., whether it is food security related or water management related; 2] quantifying the magnitude of challenge in terms of the gap between likely future production and demand for food (in land scarce regions), gap between future water demand and utilizable water supplies (in water scarce regions having sufficient land), and likely shortage in both food and water in regions that are both land and water-scarce; 3] the scope for improving food security and water supply situation in the countries that are facing these problems today, by examining the current level of utilization of water and land; and, 4] assessing the need and scope for reducing agricultural water footprint of individual countries by comparing their water footprint in diet and effective water withdrawal for production of agricultural commodities with global averages and also with effective renewable water availability in the respective countries.

2 Approach and Methodology

The paper develops three indices, viz., water adequacy index, water-land index, and water-land-pasture index, to assess the comparative situation of 153 countries around the world in terms of self-sufficiency to meet the future water needs, the agricultural production potential and milk production potential, respectively. The computed values of the latter two indices for the individual countries are used as independent variables in statistical models to explore how far they could predict the agricultural production and milk production potential respectively of the respective countries, thereby testing the robustness of the indices. Based on the nature of relationship shown by the model, different typologies of countries were established in terms of their characteristics, defined by 'water adequacy index' and 'water-land index' and their implications for water security and food security.

Subsequently, based on the current level of utilization of agricultural land for crop production, extent of withdrawal of renewable water from the natural system and the current level of utilization of irrigation potential, inferences are drawn with regard to the steps that these countries need to take to deal with future water scarcity and food insecurity challenges.
The estimates of effective agricultural water withdrawal, water footprint in diet and effective renewable water resource availability situation of 153 countries are compared to identify which countries need to reduce agricultural water footprint for reducing water withdrawal from natural systems, and which of the two options, i.e., changing consumption pattern or reducing the scale of agricultural production, is viable for a country.

The analyses extensively use global data sets on the following: 1] consumption of various food items in calorific terms by a group of 172 countries; 2] global data on water consumption per unit of calorie for various agricultural commodities, such as cereals, pluses, milk, meat products, vegetables, fruits and various dairy products, as available from Hoekstra (2012); 3] total population, geographical area, agricultural land, cultivated land, area under permanent crops and area under pasture (ha) for the group of 172 countries, as available from FAOSTAT(FAOSTAT.org), milk production from different types of livestock and dairy animals (cows, buffaloes, goat, sheep and camel); 4] annual irrigation water withdrawal volumes by a group of 155 countries; 5] estimates of green water use by a group of 155 countries estimated by Kumar and Singh (2005); 6] data on virtual water export/import by a group of 155 countries available from Hoekstra and Chapagain (2003).

The land-water index has a water index and land index. The 'water index' is based on the amount of water available to irrigate the crop land (ha) in the country, expressed as a coefficient (by dividing the total amount of renewable water by the amount of water required to irrigate the entire cropped land for 300 days in a year, using the average daily reference evapo-transpiration of the country as the basic crop water requirement). The water adequacy index is expressed as:

$$WAI = (AWR/(CA\,X\,ET_0 X\,300)\ldots\ldots\ldots \quad (1)$$

ET_0 is the average daily evapo-transpiration for the country, as a whole; CA is the cultivated area in ha. If the value of coefficient, WAI I is more than 1.0, it is taken as 1.0

This index is multiplied by the amount of cultivated land in ha per capita to obtain the land-water index. Added to this is the 'pasture land index', which is a multiple of the per capita pasture land area (ha) and a coefficient (pasture land coefficient) that captures the primary productivity of the pasture land. The value of the 'pasture land coefficient', which is used to simulate the variation in the quality of pasture land in terms of primary productivity, across countries, is decided on the basis of the rainfall and the reference evapo-transpiration, and the overall climate (tropical or temperate). Higher value for the coefficient is assigned in cases where the rainfall is high, and reference ET is low, and the climate is cold or temperate, and vice versa for low rainfall regions with high aridity, and tropical climate. The value of the pasture land coefficient chosen for the analysis varies from 0.05 for Saudi Arabia, UAE, Bahrain and Qatar to a maximum of '1.70' for New Zealand.

The effective agricultural water withdrawal of the selected countries (131 nos.) is taken from Kumar and Singh (2005). The values of effective renewable water resources are arrived by adding up the AWR (actual annual renewable water resources) and the total amount of green water used in agriculture annually, by multiplying the gross cropped land and the effective rainfall or the amount of water in the soil profile for direct use by the crops (as a function of the total average annual rainfall of the country) as per the methodology used by Kumar and Singh (2005).

The water footprint in diet is estimated on the basis of data on water embedded per unit of calorie in different types of food (cereals, milk, meat, vegetables, fruits, oil, etc.) and the average amount of calorie obtained from different types of food in different countries.

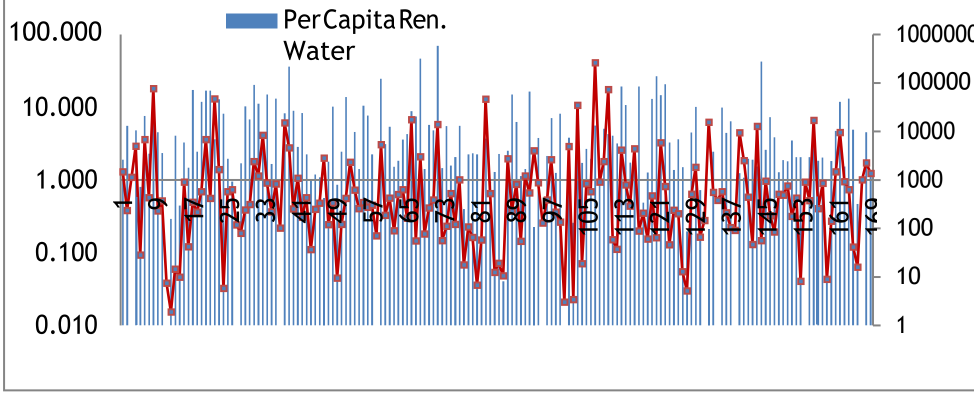
3 The Tenuous Link between 'Renewable Water' and Food & Agricultural Production Potential

As discussed earlier, the ability of a region to produce food and other agricultural commodities is very often related to the water-richness of that region, expressed in terms of renewable water availability. If a region is having sufficient amount of water resources in terms of the quantum of renewable water available, the automatic conclusion is that it can be food self- sufficient, if this water is utilized. The nexus between land and water, which define the food security and water management challenges, is not appreciated (Kumar et al., 2012; Kumar et al., 2014). This nexus operates in two ways. First: even if a region doesn't have sufficient amount of renewable water (the sum of surface water and groundwater), the availability of certain quantum of cultivable land (in the form of cultivated land and pasture land) ensures the use of water in the soil profile, available directly from the precipitation, which can be used by the crop for production. Second: even if a region is highly water-rich (say owing to excessive precipitation), the absence of sufficient amount of cultivable land can render the water un-utilizable for crop production making the region food insecure.

We have analysed the data on per capita renewable water availability in 150 countries and per capita cropped land (agricultural land). Figure 1 show the data presented in a chart. From the figure itself, one can make out that there is no relationship between renewable water resources and agricultural land. Two sample paired t test showed no relationship between per capita renewable water resources and per capita arable land. Many countries having large amount of renewable water resources (in per capita terms) have poor access to agricultural land in per capita terms. On the other hand, many countries having large amount of agricultural land (in per capita terms) have very limited water resources. There are very few countries, which are well endowed in terms of both renewable water resources and cultivable (agricultural) land. They are very unlikely to face any problems related to water and food, provided other factors of production such as labour, machinery, irrigation infrastructure and technologies (crop and water use) are available. Now we would examine how the positioning of a country vis-à-vis access to renewable water resources (including water in the soil profile available from precipitation) and agricultural land affect land and water utilization for crop production, food security scenario and water available for the environment. The land utilization would be analyzed in terms of percentage of agricultural land under crop production, and water utilization would be in terms of extent of water diversion from the hydrological system.

If a country has large amount of renewable water resources that are utilizable (say more than 20,000 m^3 per capita per year), and has sufficient

Figure 1: Per capita renewable water resources and arable land in different countries



agricultural land to feed its population, it would try and bring all that land under cultivation to meet the food needs (countries like Cambodia, Vietnam and South Korea are examples). Such countries would still have a lot of renewable water flowing into the natural sink, or neighbouring countries.

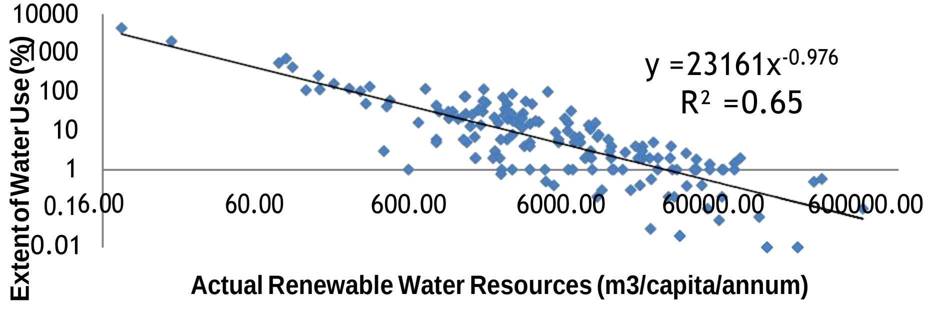
But in such water rich countries if the amount of agricultural land available is more than what is required to produce agricultural commodities for the needs of the population, it is quite likely that a lot of that land would remain un-cultivated as pasture land though the country might produce surplus food and other crops (like in the United States, Canada and New Zealand) for export. The result is that a lot of renewable water resources would remain untapped. Nevertheless, the situation of a good portion of the land lying un-cultivated (and used as pasture) can happen also when the availability of renewable water resources is less than what is required to bring the entire land under cultivation, but more than what is required to feed the population (like in the case of Australia, where the per capita agricultural land is very large, nearly 24 ha). If the agricultural land available is too little (like in Bangladesh, Indonesia or Japan), it would try to intensify land use but might still have food shortage, while a lot of blue water would be available as untapped runoff or groundwater. However, wealthy nations like Japan would import food, and leave the agricultural land fallow or convert it into pasture land.

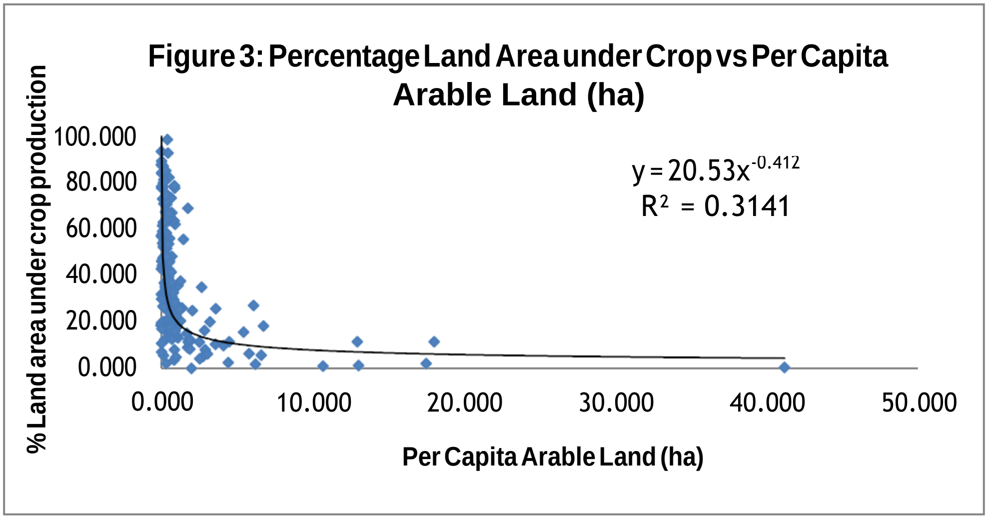
On the other hand, if a country has very little renewable water resources (less than what is required to meet the need of agricultural commodities) due to low precipitation and high aridity but has large amount of agricultural land, it would try and utilize all the water in the natural system for irrigated crop production while also using the available soil moisture optimally through rain fed production by choosing the right season and right areas. In the process, it might also mine the fossil water (like many MINAR countries, Pakistan, Iran, Iraq and Afghanistan). In this case, there would still be a lot of land left un-cultivated in the form of pasture due to shortage of water, though such land will offer low productivity.

If both renewable water resources and cultivable land are limited (say less than 1700 m^3 per capita per annum), the country would try and utilize all its renewable water resources along with water in the soil profile to increase the cropping intensity, by going for irrigated crops after harvesting rain fed crops in the same area. In such situations, there will be much less water left in the natural system and there will be too little land left un-cultivated. Such cases will be encountered in very arid regions, receiving very little precipitation. The western and north western parts of India are the best examples for this.

Therefore, in a nutshell, in countries having excessively large amount of renewable water resources, even if the amount of land available for cultivation is large (which is not often the case though), the extent of utilization of water for agricultural production and needs of other sectors, would be relatively low, limited to what is required for producing sufficient food and other agricultural commodities for the domestic population, and meeting municipal water supply

Figure 2: Degree of blue water withdrawal vs per capita renewable water resources





and manufacturing needs plus some water for producing surplus for exports. This is because of the costs involved in harnessing that additional water, with uncertain benefits from doing so. Vice versa would be true for countries having very limited renewable water resources. This is evident from Figure 2. In fact, Figure 2 shows that the actual renewable water resources determine the extent of water utilization to the extent of 65 percent. Hence, one major reason why many countries are able to leave a lot of water in the hydrological system for nature is that they have plenty of renewable water resources in per capita terms.

Whereas in countries having excessively large amount of cultivable land, even if utilizable water resources are available in plenty (which again is rarely the case), not all the land would be brought under cultivation. The area that is brought under cultivation, to a large extent, would be decided by the domestic demand for food grains and other agricultural commodities (oil seeds, vegetables, fruits, fibre, fodder and fuel-wood) and only to a limited extent by the international demand for agricultural commodities and the domestic policies for agricultural commodity trade. There are two reasons for the latter not becoming a major determining factor for area under crop production. First: there are many players in the global agricultural commodity trade. Second: the international agricultural commodity market can be highly sensitive to global agricultural outputs, which is determined by domestic production surplus. Hence, as per capita cultivable land increases, the proportion of the agricultural land that is under cultivation will keep declining as depicted by Figure 3. The R^2 value is 0.31 and the relationship is significant at 95% confidence level.

There are countries that are well endowed with ample amount of cultivable land and utilizable water resources, yet facing food shortages due to very little area under crop production, and with very small proportion of the water resources being tapped for irrigation. The extent of infrastructure development for improving water supplies is also very low in these countries. Several countries in Africa, especially in eastern Africa, fall under this category (Kumar et al., 2008; Kumar et al., 2016). There is large amount of water flowing out of these countries into the downstream countries—from Ethiopia through the Blue Nile into Egypt. As the governance in these countries improves, the extent of water utilization would increase, so be the chances for expansion in cultivated land, with the provision of irrigation facilities. The irrigation and (rural and urban) water supply situation is also likely to improve.

4 Water Footprint in Agricultural Production and Water Footprint in Diet

The importance of managing the dietary regimes for future food security and the sustainable use of natural resources has been recognised (Pimentel and Pimentel, 2003; Rockström et al., 2009; Falkenmark and Lannerstad, 2010; Foley *et al*., 2011), and consumption of animal products that are at the higher end of the food chain is found to have large environmental impacts (Steinfeld et al., 2006; Hoekstra and Chapagain, 2007). There are studies on the impact of diets on water resources for countries (Liu and Savenije, 2008; Vanham, 2013) and regions (Renault and Wallender, 2000; Vanham et al., 2013; Vanham and Bidoglio, 2014).

It is generally believed that one of the ways to mitigate water scarcity is by shifting to low water-intensive production systems, and following a dietary regime which comprises food items that are at the lower end of the food chain with lower amount of embedded water, thereby reducing the overall water footprint in agricultural production, with a consequent reduction in agricultural water withdrawal (Hoekstra and Chapagain, 2007; Mekonnen and Hoekstra, 2014, Vanham et al., 2013). Incidentally, the global data base on agricultural water withdrawal by countries, compiled by international agencies such as the FAO, essentially consist of irrigation water withdrawal by these countries. Though assessment of water footprint is separately available for blue and green water for several crops in different climatic regions in terms of volume of water per ton of production (Mekonnen and Hoekstra, 2014), water withdrawal from soil profile is not considered in the international hydrological assessments.

Hence, the focus is always on countries which draw large amount of (blue) water for irrigation, especially those in the tropical climate, to reduce their agricultural water footprint through crop water productivity improvements (Mekonnen and Hoekstra, 2014). The green water use by countries, especially those in the temperate climate, hasn't received much attention as they eventually draw lower quantum of blue water for agriculture. Secondly, the extent to which several of the low irrigation water using (rich) countries in the temperate climate depend on imports of agricultural commodities such as food grains, pulses, milk, oil and fibre to meet their domestic demand, and the source of these imports, are largely ignored to the extent that its impact on agricultural water footprint of the food exporting countries and the aggregate water footprint in the diet of the importing countries remain un-investigated. Merely looking at the irrigation water withdrawal of the latter group or water footprint in dietary intake of the former group to address the issue of rising agricultural water footprint within the limited domain of the country of interest would only be misleading in terms of what options are available for countries to reduce their water footprint and its likely impacts.

In countries which have large amount of crop land (in per capita terms) and in countries with temperate climate, the water withdrawal from soil profile (or green water use) constitutes a major proportion of the effective water withdrawal for agricultural production (Kumar and Singh, 2005). It is to be kept in mind that green water use is a major component of the hydrological balance, and change in green water use would affect the blue water flows (in the form of runoff and groundwater recharge) in the natural hydrological system. Ability to tap larger amount of green water (by bringing large areas of the cultivable land under production and adjusting the cropping season to match the availability of precipitation for soil storage) reduces irrigation requirement for crop production (Falkenmark, 2004). Therefore, it is important to look at this as a factor determining 'effective water availability' as well as 'effective water withdrawal' in agriculture.

Kumar and Singh (2005) provided estimates of effective water withdrawal in agriculture for 133 countries. It shows a wide range in the estimates amongst countries--from a meagre 37 m^3 per capita for Malta to 18,965 m^3 per capita for Australia, i.e., nearly 1: 500. The regression between green water use by 133 countries and the effective agricultural water withdrawal (sum of irrigation water withdrawal and green water use) shows a very high correlation (R^2=0.97), meaning that at the global scale, the effective water use for agriculture is determined by the extent of rain water use--area under the crop, and the rainfall conditions.

Detailed assessment of water footprint at the national level had been done for several European countries, e.g. (Aldaya et al., 2008; Van Oel et al., 2009), and countries outside Europe, e.g. (Verma et al., 2009; Bulsink et al., 2010). Detailed water footprint analyses on a global scale have been conducted for selected products, e.g. wheat (Mekonnen and Hoekstra, 2010) and rice (Chapagain and Hoekstra, 2011). We estimated water footprint of diet for 153 countries based on the data on average amount of calorie intake from different types of food and the water footprint in every unit calorie from these food types, for each country. Water footprint in production of crops and livestock products is also a function of climatic factors and production practices (Mekonnen and Hoekstra, 2014). However, for the purpose of the study, average values of water footprint per unit of calorie intake for different types of food were considered. As per our estimates, the water footprint of food consumption ranges from a lowest of 481 m^3 per capita for Zambia to 2,235 m^3 per capita for Argentina. In order to examine whether high agricultural water withdrawal is driven by domestic consumption behaviour, we have run a regression between the two.

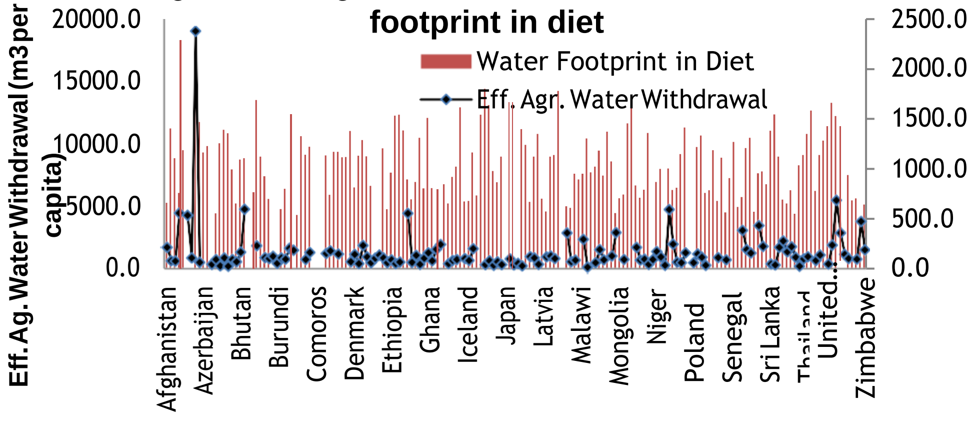
Our analysis suggests that there is no relationship between dietary water footprint of a country and its effective agricultural water footprint (eff. agricultural water withdrawal) (Figure 4), as shown by the two sample paired t test.

Many of the countries which actually withdraw very little amount of water from the natural system for crop production in per capita terms in the range of 240-400 m3 per capita (viz., Germany, United Kingdom, Sweden, Switzerland, North Korea, South Korea, Israel, Jordan, Finland, France and Japan), have very high water footprint in diet. Even in China, which maintains a relatively low agricultural water withdrawal rate (670 m^3 per capita), the water footprint in the diet of its people is high (1140 m^3 per capita). These countries import grains for direct consumption and as feed for dairy animals and livestock meant for meat production. They also import large quantities of vegetables, fruits and flowers. Barring Israel, most of these are water-rich countries. But the scope of increasing domestic production of agricultural commodities to reduce the import does not exist in these water-rich countries due to land scarcity. At the same time, if reduction in imports is accepted as a strategy to reduce dietary water footprint, it would help the food exporting countries only if they experience resource depletion as well as water scarcity. For those, which are water-scarce (like China), changing food habits would help reduce domestic water withdrawals if import is continued.

Whereas there are many countries which effectively use excessively large quantities of water for agriculture such as Afghanistan, Angola, Argentina, Bolivia, Ecuador, Gabon, Guinea, Iran, Madagascar, Mozambique, Paraguay, Peru, Somalia, Sudan, Syria, Tajikistan, Uruguay, Uzbekistan and Zambia but have relatively low water footprint in their dietary intake--mostly less than 1000 m^3 per capita per annum. Many of them export agricultural commodities. Of these countries, the focus should be on those which are water-scarce, such as Afghanistan, Iran, Tajikistan, Uzbekistan, Somalia, Sudan, Syria and Zambia. These countries will achieve much not by changing their diet, which has a low water footprint, but by reducing export of agricultural commodities. However, this will be at the cost of their export economy. The fact that a lot of virtual water flows from water scarce and land rich countries to water-rich and land scarce countries was also established by Kumar and Singh (2005).

Also, there are countries which have very high agricultural water withdrawal and also maintain diets which have high water footprint, such as Australia, Argentina and Canada and to an extent the United States of America. Amongst these, Australia and United States (many parts of which experience severe water scarcity and droughts) can reduce their agricultural water withdrawal provided the countries (especially in Europe) importing agricultural commodities--dairy and livestock products, vegetables, fresh and dry fruits, etc., from these countries change their consumption patterns. Also, the very countries exporting these agricultural commodities can change their consumption patterns.

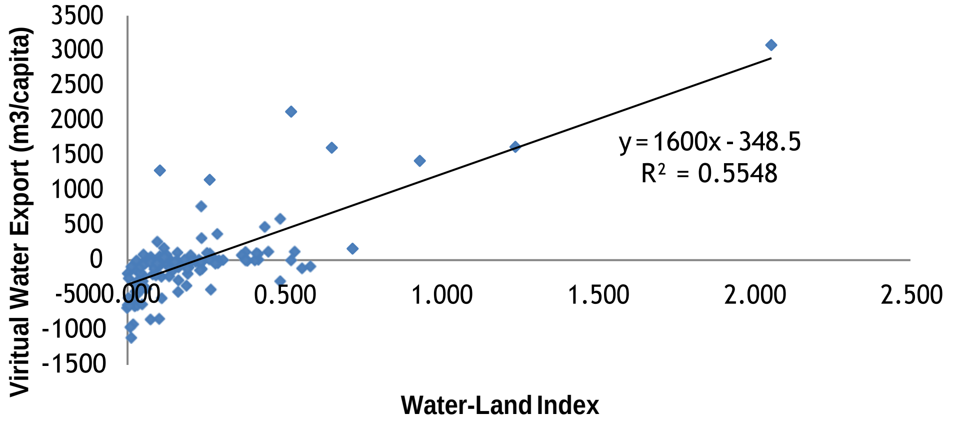
Figure 4: Eff. agricultural water witdrawal and water footprint in diet



5 Which Countries have Plenty of Water for Future Crop Production?

Kumar and Singh (2005), which analyzed the determinants of global virtual water trade found that virtual water export from a country is a direct function of access to arable land, expressed in terms of gross cropped area, and explained this phenomenon using the concept of ‘effective agricultural water withdrawal’, the sum of irrigation water withdrawal and water use from the soil profile, which increased linearly with per capita gross cropped land. They further

Figure 5: Virtual water export vs water-land index



developed a framework according to which the country which has largest amount of agricultural land with sufficient amount of water to bring it under crop production would have the highest advantage in terms of producing agricultural surplus and export. However, a country which has the same amount of water, but with very little agricultural land, will not enjoy the same advantage. On the contrary, a country with less amount of renewable (blue) water, with the same amount of agricultural land as that of the first country, with be relatively better off in terms of agricultural production scenario. This essentially means that beyond a point having large amount of water disproportionately higher than the amount of cultivated land bring no added advantage.

We developed a composite water-land index, which captures two important dimensions of future agricultural production potential of a country, viz., adequacy of water to bring the available cultivated land under intensive irrigated production (water adequacy index) enough for 300 days in a year, and the total amount of cultivated land in per capita terms, into a composite index, by multiplying them. The water adequacy index was estimated as a ratio of the total amount of renewable water resources and the amount of water required for irrigating the entire cultivated land for a period of three hundred days. The maximum value of water adequacy index is 1.0, wherein a computed value above '1.0' is treated as one. The value of the composite (water-land) index varies from 0.0 (for Solomon Islands) to 2.056 for Australia. The regression run between water-land index and the per capita virtual water export showed a linear relationship with an R^2 value of 0.55 (Figure 5). The relationship is significant at 95% confidence level. Increase in value of water-land index meant greater agricultural surplus after domestic consumption, and reduced value of the index meant production deficit to meet the domestic consumption needs. This strong relation means that water-land index is robust enough to capture the agricultural production potential of a country.

There are 21 countries from around the world having water resources (having a water adequacy index of 1.0) which can be used to expand the cropped land and boost agricultural production. They are Argentina, Belie, Benin, Bolivia, Brazil, Myanmar, Canada, Finland, France, Guatemala, Hungary, Lithuania, Nicaragua, Paraguay, Romania, Sweden, Thailand, USA and Uruguay (Table 1). They are not doing so because of several reasons, including marginal quality of the land available for future harvest, high cost of production, lack of domestic demand for the produce, and therefore the need to tap additional export market, etc. These are countries which have excessively large amount of renewable (blue) water in per capita terms and smaller fraction of their agricultural land under crop cultivation, leaving the remaining land under permanent crops and pastures. Essentially, these are also most likely to be countries which have large amount of agricultural land in per capita terms (ranging from 0.49 for US to 1.24 for Canada), if we go by the model presented in Figure 3. Their water-land index values range from 1.239 for Canada to 0.104 for Guatemala. So, merely by bringing a small portion of this agricultural land under crop cultivation, they are able to meet their needs for exports as well as domestic consumption. All of them are virtual water exporting countries.

Table 1: Irrigation Water Utilization in Countries having Adequate Amount of both Arable Land and Water Resources

Name of Country	Eff. Renewable Water Resource per Capita (m^3)	Effective Agricultural Water Withdrawal (m^3 per capita)	Water Footprint per Capita (m^3)	Actual Irrigation Water Use (m^3/capita)	Irrigation Potential Utilized (for Water rich countries)	Per Capita Cultivate d Land (ha)	Virtual Water Export (m^3/capita)
Argentina	24630	4213.5	2235.2	588.3	6.54	0.934	1418.15
Belize	71760	655.6	994.3	0.9	0.04	0.238	312.31
Benin	4280	483.4	655.2	31.1	0.90	0.264	92.68
Bolivia	73950	4683.4	1106.6	142.5	3.54	0.378	118.04
Brazil	47150	1771.7	1691.6	217.8	6.39	0.365	71.43
Myanmar		921.9		692.5	35.07	0.203	72.47
Burundi	2530	357.2		28.5	3.12	0.098	-0.69
Canada	92852.5	1555.4	1496.2	137.0	3.58	1.239	1623.41
Finland	21420	334.0	1532.7	12.8	0.82	0.417	90.43
France	3782.5	446.7	1542.8	66.8	3.99	0.288	376.35
Guatemala	9220	551.3	809.0	145.1	11.98	0.104	1283.04
Hungary	11022.5	669.2	1023.9	239.7	9.58	0.439	475.59
Lithuania	8022.5	746.6	1138.4	5.7	0.16	0.719	162.61
Nicaragua	36580	1632.1	832.7	218.6	7.15	0.255	102.47
Paraguay	60440	4662.9	1004.6	65.3	0.86	0.653	1605.82
Romania	10110	1083.8	1217.7	587.9	25.15	0.412	97.93
Russia	32790	836.1	1333.8	93.3	3.14	0.833	-70.40
Sweden	19857.5	296.4	1380.8	29.3	2.32	0.276	31.50
Thailand	6900	1689.8	786.4	1372.9	52.61	0.236	770.86
United States	11485	1825.7	1662.7	712.0	23.61	0.488	589.85
Uruguay	44990	5407.5	1531.0	914.7	17.90	0.522	2128.01

This is in contrast to countries like India, which have utilized nearly 90% of the agricultural land for (temporary) crop cultivation, given the very small amount of agricultural land per capita, resulting in excessively high anthropogenic pressure on land for survival. Future growth in population in these countries is likely to result in expansion in arable (cultivated) land. However, this is unlikely to happen in all cases, as population growth is either nil or negative in many of these countries that are developed.

Now, there are 39 countries which do not have sufficient amount of renewable water resources which can be used to bring all the cultivated land under irrigated production. Their per capita cultivated land area is in the range of 0.003 (Kuwait) and 2.069 (Australia). Their water adequacy index is less than one (Table 2). This means, even if all the utilizable water is harnessed and diverted for irrigation, it won't be sufficient to meet the irrigation demand of the entire cultivated area (not crop land). The low value of water adequacy index is also a reflection of the good amount of cultivated land and high irrigation water demand. It is important to know how many of these countries are producing sufficient amount of food, and if not, whether there is possibility of increasing agricultural production in these countries.

For this, we looked at the current level of utilization of irrigation water in these countries. In spite of having low water adequacy index, twelve out of these 39 countries use only a small fraction of their irrigation potential. They are Australia, Denmark, Burkina Faso, Sudan, Ukraine, Cuba, Moldova, Nigeria, Malawi, Uganda, Zimbabwe and Afghanistan. Even with a small volume of blue water, they are able to produce surplus agricultural outputs (cereals in the case of Australia and dairy products in the case of Denmark) by tapping soil water, as they are endowed with large amount of agricultural land in per capita terms. If they expand irrigation, they would be able to increase their production manifold. However, their ability to trade these agricultural commodities globally depend largely on their cost of production and international market trends. All other countries are virtual water importing countries.

Among these 39 countries, there are seven countries whose water use far exceeds the renewable water availability. In fact, most of them are mining fossil groundwater. They are Jordan, Kuwait, Libya, Israel, Qatar, Yemen and Pakistan. Yet, they are heavily dependent on virtual water imports. One of the reasons is that they have very little arable land that is productive and the rainfall is also too low. We can therefore consider the remaining 20 countries, where irrigation expansion through infrastructure development is possible to boost

Table 2: Irrigation Water Utilization in Countries Having Limited Water Resources, but adequate amount of Cultivated Land

Name of Country	Effective Renewable Water Resource per Capita (m^3)	Effective Agricultural Water Withdrawal (m^3 per capita)	Modified Water Adequacy for Crop Land	Actual Irrigation Water Use (m^3/capita)	Irrigation Potential Utilized (%)	Per Capita Cultivated Land (ha)	Virtual Water Export (m^3/capita)
Afghanistan	3385	1624.9	0.859	886.5	42.5	0.267	8.75
Algeria	848	532.3	0.145	131.5	37.4	0.196	-349.88
Australia	42822.5	18965.9	0.982	951.3	4.8	2.094	3079.16
Barbados	376	146.5	0.679	75.1	31.7	0.036	-655.75
Bulgaria	3327.5	810.6	0.944	239.9	11.0	0.443	6.72
Burkina Faso	1605	734.0	0.147	62.7	8.4	0.356	81.45
China	2530	669.6	1.000	340.9			-15.52
Cuba	4080	1103.6	0.960	505.8	18.8	0.319	3.26
Denmark	1517.5	474.8	0.587	101.5	11.3	0.448	1148.46
Eritrea	2410	1009.1	0.574	72.7	6.2	0.160	-18.98
Ethiopia	2055	406.4	0.826	39.3	2.9	0.170	-5.22
India	1340	740.7	0.752	559.6	64.8	0.129	34.53
Iran	2515	1535.9	0.702	1055.3	67.0	0.233	-105.10
Israel	315	256.2	0.518	209.8	104.9	0.039	-915.09
Jordan	241	235.5	0.422	160.2	125.2	0.026	-956.71
Kenya	1605	706.7	0.560	34.4	4.6	0.133	-27.55
Kuwait	35	142.5	0.113	119.4	1866.3	0.003	-682.37

Libya	244	930.0	0.018	824.9	972.7	0.288	-258.60
Malawi	1810	485.3	0.542	80.2	7.2	0.233	74.70
Mali	9110	2286.2	0.810	648.8	10.9	0.474	-8.14
Malta	145	37.4	0.697	25.8	24.8	0.020	-1109.39
Moldova	3232.5	622.8	0.881	177.1	8.1	0.512	120.92
Morocco	1505	950.7	0.339	406.5	54.6	0.244	-202.72
Niger	3500	670.9	0.123	44.5	2.1	0.210	-43.52
Nigeria	2820	610.2	0.782	198.5	11.0	0.944	32.03
Pakistan	1600	1305.9	0.909	1206.0	106.2	0.121	-0.61
Qatar	131	410.3	0.738	372.5	541.5	0.006	-540.70
Rwanda	810	207.7	0.685	3.6	0.7	0.104	-11.82
Senegal	4470	804.8	0.651	154.1	5.1	0.251	-284.37
Somalia	3985	2984.9	0.664	386.8	35.0	0.114	-32.77
South Africa	2932.5	1449.4	0.377	264.5	29.8	0.231	-127.19
Sudan	4105	3372.8	0.121	1181.3	78.5	0.857	51.17
Tanzania	3640	1270.4	0.859	56.2	2.9	0.273	-26.83
Togo	3760	844.6	0.611	18.2	0.8	0.380	-145.52
Tunisia	965	716.0	0.166	236.0	64.1	0.264	-424.86
Uganda	3040	573.3	0.936	5.6	0.3	0.196	6.47
Ukraine	3560	1016.8	0.753	394.6	17.0	0.710	121.36
Yemen	733	682.4	0.283	370.5	233.9	0.050	-92.02
Zimbabwe	2810	1425.6	0.378	180.9	14.6	0.316	40.62

agricultural production. They include countries such as Algeria, Armenia, Barbados, Bulgaria, Cuba, Eritrea, Ethiopia, Iran, India, Kenya, Mali, Malta, Morocco, Niger, Rwanda, Senegal, South Africa, Tanzania, Togo and Tunisia.

Now there is a third category of countries, 69 in total, which have 'water adequacy ratio' higher than one, and therefore considered as one (Table 3). In some cases, it is because they have very little cultivated land, and not because they have very large amount of renewable water resources. As a matter of fact, out of the 69 countries, only four countries have more than 0.5 ha of cultivated land per capita and 29 countries have less than 0.10 ha of cultivated land per capita. Due to severe water shortage, some of them bring a small portion of their agricultural land under cultivation of temporary crops (Bahrain, Oman, etc.). Nevertheless, many others have a large amount of renewable water, with very limited agricultural land and cultivated land (For instance, Bangladesh, Jamaica, El Salvador, Dominican Republic, etc.). But their distinct difference from countries such as United States, Argentina, Brazil and Canada (which have both large amounts of cultivated land and water resources) is that they have disproportionately lower amount of arable land than water resources. This factor reduces their water-land index values. As a result, they are virtual water importing countries. Their irrigation potential utilization, estimated as a ratio of the total amount of irrigation water withdrawal (m^3 per capita) against the total amount of required to irrigate the cultivated land for nearly 300 days in a year and expressed in percentage terms, ranges from as low as 0.1 (percent) to 451 (percent).

As evident from these estimates, there are a few countries which actually divert more water than what is required by the reported cultivated land. They are Bahrain, Bangladesh, Ecuador, Egypt, Japan, Oman, Suriname, Tajikistan and Uzbekistan. This excessive diversion could be because of the following reasons: 1] the actual water diversion for irrigation could be much higher than the consumptive water use we have considered, by using the figures of average ET; and, 2] some countries could be using perennial crops, due to which the total ET requirement of crops would be higher than what we have considered, which is for only 300 days. As regards the first point, for crops like paddy, a large amount of water is applied to the field to inundate it, which is far in excess of the crop ET requirements, and in certain cases, a lot of water would be required in hyper arid climates, to meet the non-beneficial consumptive uses (such as barren soil evaporation). Yet, they are dependent on food import. Unless, the crop yields increase substantially, there is no way these countries can become food self-sufficient.

As Table 3 shows there are 60 countries which are not fully utilizing the irrigation potential and remaining as net importers of agricultural commodities. Many of them are developing countries with limited economic power, and want to boost their agricultural production. These countries can invest more in water resources development for irrigation intensification and thus become self-sufficient in agriculture, depending on the cost of water resources development and the productivity of the land which is under cultivation. However, cropping to cover 300 days out of 365 days in a year is not an easy task. In any case, many of the developed countries (such as Germany and Italy) in this list will not be in a position to expand or intensify irrigation due to scarcity of labour and the high cost of production of crops. Also, in many countries in northern Europe and in North America, the land is covered with snow for several months in a year, reducing the ability to go for intensive crop production.

6 Linkage between Agricultural Land, Cultivated Land and Milk Production

From the above discussion, it is clear that having plenty of renewable water does not guarantee large agricultural production. Nor would plenty of cultivable land guarantee large-scale agricultural production. In fact, some countries have large amount of land, classified under agricultural land (for instance, Kazakhstan and Mongolia). But the land is of poor quality and at best is suitable for grazing (in Mongolia, even the pasture land is of poor quality, capable of producing grasses only for four months). What matters is the amount of land that is cultivated.

Without having water to irrigate and nutrients to supply to the soils, such marginal lands will not be able to produce much biomass due to poor crop yields. The interaction between renewable water resources and cultivated land and between precipitation and pasture lands to produce biomass outputs is through a complex web, with climate at the backdrop. The amount of water required to irrigate a unit area of crop land (for intensive cropping to cover the whole year) is determined by effective precipitation and climate. The climate determines the ET and effective precipitation decides the amount of irrigation, for a given crop ET. If adequate amount of water is available to irrigate the cropped land, the overall production would depend on the total amount of cropped land. If this is not available, the productivity per unit crop area would decline. If more water (than what is required to irrigate the crop) is available, it would not lead to increased

Table 3: Irrigation Potential Utilization in Countries Having Limited Cultivated Land, but having Sufficient Water to Irrigate

Name of the Country	Eff. Renewable Water Resource per Capita (m^3)	Effective Agricultural Water Withdrawal (m^3 per Capita)	Water Footprint per Capita (m^3)	Actual Irrigation Water Use (m^3 per Capita)	Ref. Evapo-transpiration (mm)	Virtual Water Export (m^3 per Capita)	Per Capita Cultivated Land (ha)	Irrigation Potential Utilized (for Water rich countries)
Albania	13420	566.2	1404.9	312.9	2.4	-102.79	0.197	22.41
Angola	14880	4378.7	758.9	16.0	3.9	-31.14	0.235	0.59
Armenia	3772.5	779.2	1301.4	510.7	2.80	-81.58	0.152	18.50
Bahrain	160	259.4		254.9	6.8	-640.82	0.003	438.48
Bangladesh	8210	663.1	553.2	592.6	3.0	-43.81	0.050	131.91
Belarus	6587.5	774.8	1392.1	83.7	1.5	-89.17	0.584	3.10
Belgium	1882.5	123.9	1357.7	10.8	1.7	-846.22	0.075	2.77
Bhutan	41650	1246.4	1093.6	511.4	2.2	-34.01	0.132	59.47
Burundi	2530	357.2		28.5	3.1	-0.69	0.098	3.12
Cambodia	33360	791.7	599.7	340.3	3.4	-11.08	0.274	12.09
Cameroon	18150	679.4	802.2	50.2	3.4	-0.12	0.293	1.70
Central African Rep.	38320	1407.1	884.4	0.3	3.7	0.05	0.407	0.01
China	2530	669.6	1140.1	340.9	2.1	-15.52	0.076	72.41
Colombia	48590	1212.8	1223.0	118.4	3.2	-161.34	0.033	37.16
Congo, Dem. Rep.	23790			0.1	3.3	-3.69	1.663	0.00

Costa Rica	27280	1151.0	1136.6	383.2	3.8	-221.19	0.053	63.11
Cote d'Ivoire	6110	1354.3	740.3	38.5	3.4	-49.45	0.149	2.53
Djibouti	1470	1059.9	812.6	11.3	5.1	-189.41	0.003	27.02
Dominican Rep.	2790	317.9	1130.7	5.8	3.9	-6.06	0.079	0.63
Ecuador	32960	1774.9	1288.4	1124.9	2.8	47.04	0.077	172.42
Egypt	835	873.4	1126.9	857.7	4.5	-293.22	0.035	180.56
El Salvador	4100	397.1	829.0	123.5	4.2	-236.65	0.110	8.93
Equatorial Guinea	52030	752.7		2.3	2.7	-22.69	0.238	0.12
Estonia	10562.5	779.7	1205.9	5.8	1.4	-302.22	0.488	0.28
Fiji	34290	635.8	962.6	62.3	3.2	-364.17	0.190	3.44
Gabon	125710	4346.5	895.3	41.7	2.6	-192.46	0.194	2.76
Gambia, The	5882.5	427.8	694.2	15.8	5.3	-128.07	0.239	0.42
Georgia	13150	988.8	867.4	410.6	2.2	-52.29	0.092	66.59
Germany	2027.5	269.3	1312.5	113.4	1.7	-159.91	0.143	15.51
Ghana	3240	763.4	802.9	13.2	4.1	-29.04	0.190	0.56
Greece	7472.5	1200.2	1511.9	593.1	3.0	-18.72	0.228	28.76
Guinea	21860	1868.1		85.1	4.6	-4.94	1.241	0.49

Guinea-Bissau	27620	1471.1	744.1	187.6	4.0	-8.12	0.030	53.02
Haiti	1870	323.0	653.8	119.2	3.5	-55.70	0.106	10.75
Honduras	14000	579.3	920.6	110.3	3.9	-87.38	0.131	7.20
Indonesia	13000	581.5	678.3	365.2	3.2	-111.79	0.097	39.01
Italy	3610	550.0	1639.8	347.2	2.4	-544.92	0.110	44.23
Jamaica	3720	204.7	978.5	7.7	3.6	-174.22	0.044	1.64
Japan	3440	477.5	867.1	436.2	2.0	-645.69	0.034	212.71
Korea, North	1520	232.6	1159.5	190.4	2.2	--30.89	0.048	61.29
Korea, South	3580	352.7		224.0	2.4	-632.08	0.061	50.74
Lao, PDR	58030	879.2	671.1	523.3	3.1	-19.75	0.219	26.06
Latvia	16290	790.5	1122.6	16.6	1.5	-118.93	0.558	0.66
Lebanon	1280	276.7	1350.8	215.6	3.5	-446.11	0.027	75.74
Liberia	67380	871.4	572.2	19.7	3.4	-27.08	0.123	1.60
Madagascar	20800	2776.6	625.9	950.3	3.4	-9.57	0.161	57.36
Malaysia	23700	593.6	952.3	246.4	3.0	-485.41	0.033	82.36
Mauritius	2340	411.7	1024.2	315.4	2.9	-407.10	0.062	57.89
Mexico	5275	1457.5	1184.0	624.5	3.7	-122.56	0.192	28.96
Mozambique	14100	2809.1	556.9	31.7	3.8	-16.80	0.205	1.37
Nepal	8440	653.9	742.1	436.3	2.2	-1.26	0.080	82.16
Norway	84180	284.7	1359.4	51.6	1.1	-450.52	0.163	9.28

Oman	490	661.1		523.3	5.2	-650.29	0.007	451.17
Panama	47380	860.5	999.0	81.9	3.4	-37.26	0.145	5.62
Papua New Guinea	137460	205.9		0.2	3.3	-99.87	0.043	0.05
Peru	95170	1891.8	786.9	650.8	3.0	-230.30	0.134	54.70
Philippines	6080	445.3	810.8	284.5	3.2	-50.82	0.057	51.57
Poland	1960	392.2	1147.3	34.9	1.6	-42.69	0.290	2.59
Portugal	7195	1188.3	1412.9	878.5	2.5	-838.25	0.103	112.98
Spain	3355	1179.6	1313.2	615.0	2.9	-419.98	0.268	26.13
Suriname	278360	1705.6	973.5	1493.6	3.4	173.45	0.118	124.74
Switzerland	7690	228.3	1545.7	7.0	1.6	-300.32	0.051	2.96
Tajikistan	3185	2156.8	691.2	1785.4	2.7	5.52	0.109	203.21
Trinidad & Tobago	3050	118.3	1037.0	15.5	3.5	-553.03	0.019	7.94
Turkey	3460	888.2	1349.2	433.0	3.0	-48.31	0.281	17.11
United Kingdom	2750	289.9	1426.3	4.7	1.3	-50.12	0.097	1.22
Uzbekistan	2555	2795.1	1372.2	2228.8	3.4	-29.34	0.153	141.92
Venezuela	48080	1080.5		167.5	3.8	-218.63	0.093	15.72
Zambia	13210	3707.3	480.8	133.7	4.3	9.69	0.262	3.93

production, but increase the availability of water for ecological uses. The climate influences farming to a great extent also by allowing or disallowing certain types of crops and dairy animals and their varieties in an area.

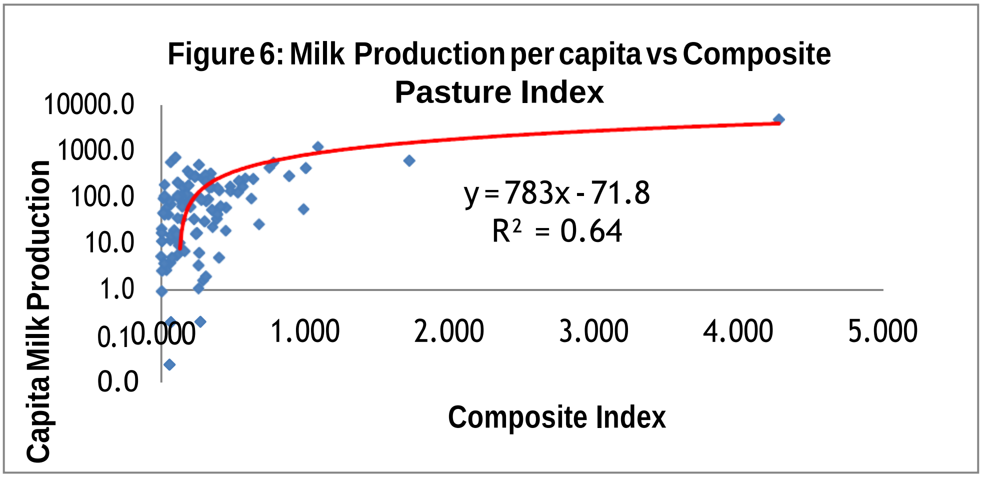
Pasture land availability determines the livestock and dairy outputs. Very importantly, in any country, the expansion in arable land (cropped land) is at the cost of pasture land, as the amount of agricultural land in a country would either be static or keep reducing over time, with urbanization and industrialization and more built up area. As Figure 3 indicates, several countries, which have large per capita cultivable land, have large amount of pasture land and vice versa. India is an illustrative example. The average per capita pasture land in India is as low as 0.0085 ha, whereas in the United States, it is 0.795 ha, nearly 100 times that of India. The productivity of pasture land is a function of climate and precipitation. Year round precipitation would ensure high productivity of pasture land with grasses, if climate is moderate.

The best production system that illustrates this complex web of interactions is dairy production. Dairy animals survive on grazing in pasture land, stock feeding (of grasses of other fodder crops either from pasture land or from crop land) or both. In order to test the hypothesis about this complex web of interactions (illustrated above), we have developed a composite index for dairy production, which has a water-land nexus index and pasture land index.

The value of the coefficient is determined on the basis of the total annual precipitation and the average daily evapo-transpiration, for obtaining a composite index for milk production capability. Higher the rainfall and lower the ET0 value, higher will be the value of the coefficient. The highest value of the coefficient assumed is 1.7 (for New Zealand) and lowest value was 0.05 for hyper-arid and desert countries (UAE, Saudi Arabia, Kuwait, Bahrain, Qatar, Yemen, Egypt, Oman, Libya, Algeria) with very low rainfall (200mm and below). A high value of the coefficient indicates better primary productivity of the pasture land to produce biomass.

The full influence of climate in deciding the milk production potential of a region, however, could not be captured in the composite index. There is obvious difference in the type of dairy animals which a particular climate can support. For instance, cold climate is very suitable for high yielding breeds of cows (which are found in Northern, Central and Eastern Europe, the Americas and New Zealand), and the hot and arid tropics are not suitable for these animals. Buffaloes are adapted to both hot and arid, and hot and humid tropical climate, and are seen in countries such as India, Pakistan, China, Nepal, Bangladesh, Afghanistan, Iran, Iraq and some countries in Africa and Latin America.

The regression is run between per capita milk production and the composite index of



milk production capability. The value of the composite index ranged from a lowest of 0.002 to the higher of 2.50. The per capita milk production is based on the total milk yield from five different types of dairy animals, viz., cows (both crossbred and indigenous), buffaloes, goat, sheep and camels (mainly in the Middle-East) for the year 2013. The regression produces an R2 value of 0.64, which means the composite index explains milk production to the extent of 64 percent and the relationship is significant at 95% confidence level. This means that the index is realistic. When regression was run the computed value of composite index, having water index merely as a function of the renewable water, no relationship emerged. This once again validates our assumptions in estimating water index of the land-water nexus index.

As seen in Figure 6, with increase in the value of the composite index, the per capita milk production also increases linearly. However, two trend lines clearly emerge, one with steep slope and the other with mild slope. Most countries on the steep gradient line are developed countries, experiencing cold and temperate climate. Most of the countries falling on the mild gradient line are the developing countries, under hot tropical climate. This differential productivity is mainly due to the differences in climate, which changes the production potential of the land and production technologies, and dairy production practices.

The countries which fall on the steeper gradient line, which we call the "technical efficiency frontier", generally have higher milk production efficiency. This can be due to the following facts: 1] favourable climatic conditions (high humidity, low temperature and higher incident solar energy) leading to production of higher biomass with lower transpiration, resulting in higher crop/fodder/grass yields and physical productivity of water; 2] adoption of certain high yielding varieties of cows such as Holstein Friesian and Jersey, which are better suited to the cold and temperate climates[1]; and 3] high energy conversion ratios due to stock feeding of animals. A closer look at the regression shows that India, whose composite index value is a mere 0.113, maintains a per capita milk production of 113 kilogram per annum, whereas the value predicted by the model is only 16.3 kg/capita per annum. Therefore, India is on the "technical efficiency frontier", with a production 7 times higher than the potential predicted by the model. On the other hand, New Zealand, whose composite index value is 4.25, produces 4836 kg/year, just 50 percent higher than value (3254 kg/year) predicted by the model. Therefore, in spite of having several disadvantages vis-à-vis the production environment (in terms of climate, rainfall, pasture land availability and amount of cultivated land) India is a super performer when it comes to dairy production. The model can be strengthened if the climate factor is taken into account.

7 Findings

1. The paper has analysed the food security and water management challenges facing the world, from the point of view of individual nations, but does so by delinking the food security challenges from water supply challenges. This is based on the premise that assessing the food security scenario purely from a water resource perspective gives a distorted view of the food security challenges facing a country. Similarly, assessing the water management challenges purely from the point of view of renewable water resource availability also can be misleading.

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[1] Research in Rajasthan in western India shows that the milk yield was negatively correlated with and inter-calving period was positively correlated with maximum daily temperature, maximum humidity, and maximum temperature/humidity index and sunshine hours, for cross breeds of Holstein Friesian cows.

2. The paper also critically examined the validity of the arguments for countries to reduce their agricultural water footprints based on data on their irrigation water withdrawals and water footprint in their dietary intake. This was done by taking into account the fact that irrigation is just a component of the total water withdrawal for agriculture, water in the soil profile is a major component, which only a few countries have the comparative advantage of accessing, and many countries maintaining high diet with high water content actually import large amounts of food.

3. In the wake of the recent research findings that 'agricultural land availability' can be a major constraint to food production in many water rich as well as water scarce countries, and that some water scarce countries enjoy a comparative advantage in producing surplus for trade which determines the direction in which virtual water flow takes place globally, it is imperative to have separate criteria for assessing water self-sufficiency, magnitude of future water scarcity and food security challenges facing a country.

4. The composite 'water-land index' developed for this study captures the adequacy of water to bring the entire cultivated land under irrigated production (water adequacy index, whose maximum value is 1.0), and the amount of cultivated land per capita (ha). Subsequently, we have also derived a composite index, which adds up the water-land index hence computed, and the amount of quality pasture land (pasture land per capita X pasture land coefficient) available for grazing and grass production to predict the maximum per capita milk production in different countries.

5. In this study, we have analysed global data sets consisting of country-wise renewable water resources, irrigation water withdrawal, cultivated land, pasture land, area under permanent crops, irrigated land area, milk production and virtual water trade, and our own estimates of the extent of utilization of irrigation potential, water foot print in crop production and food consumption and green water use in agriculture. In addition, we have computed 'water adequacy' of countries to bring the current cultivated land under irrigation; a composite 'water-land index' to simulate the agricultural production potential of a country in per capita terms and another composite index of water, cultivated land and pasture land to simulate the milk production potential of a country in per capita

terms for 152 countries, using the indices we developed for the purpose and the relevant global data set.

6. Our analyses show that per capita agricultural land availability is an important factor determining how much of the agricultural land would be used by countries for cultivation, how much would be left as permanent pastures, when water is available in plenty. Countries, which have high per capita agricultural land, use a small proportion of that land for production of temporary crops, leaving most as pasture land for grazing and fodder grass production. It also shows that certain countries are able to leave large proportion of the 'blue water in their territory into the natural hydrological system as ecological flows, merely because they have large amount of renewable water resources, disproportionately higher than the cultivated land.

7. Analysis of agricultural water footprint and water footprint in diet for 150 countries shows that there is hardly any relation between the two. Many countries, where people maintain diet with very high water content, actually do not produce much of the agricultural commodities domestically and instead import. Reduction in dietary water footprint through change in consumption pattern would help only if the countries that export food to these countries experience resource depletion. On the other hand, in many countries, which leave a very high water footprint in their agricultural production, the water footprint of the average diet of the population is quite low, and the surplus production is exported. Some of these countries are Afghanistan, Iran, Tajikistan, Uzbekistan, Somalia, Sudan, Syria and Zambia. Reducing water footprint in their agriculture can be only through growing crops in smaller area and this will be at the cost of their economy and livelihoods. There are many countries which leave a high water footprint both in their diet, as well as in their agricultural production. However, only a few of them (Australia and United States of America) experience water-scarcity. They need to change their food habits to reduce water footprint in agriculture, while also reducing their agricultural exports. But, for the latter to happen, the countries which import food from them need to change their consumption pattern.

8. The modelling of virtual water trade --volume of export and import of agricultural commodities in terms of amount of embedded or virtual water in them--, a parameter which indicates the deficit/surplus in

agricultural production of a country, across the world involving 152 countries, using the 'water-land index' and 'per capita virtual water export' showed that water-land index could be a significant variable explaining virtual water trade of nations through agricultural commodities. When the value of the water-land index increased, the agricultural export from the country (in terms of water embedded in the agricultural commodities) increased linearly. The index explained virtual water trade to an extent of 55 percent. The composite index consisting of 'water adequacy index', per capita cultivated land, per capita pasture land and richness coefficient for the pasture land explained milk production potential of countries (per capita terms) to the extent of 64 per cent.

9. Further, availability of large amount of renewable water resources (in per capita terms) doesn't mean water adequacy for irrigating all the cultivated land (water adequacy ratio < 1.0) if per capita cultivated land is large and the country could face severe water shortages, as the situation in Australia illustrates. However, this does not have implications for agricultural production, as it might be producing large surplus for export. As situation 10 countries illustrates, availability of large amount of renewable water resources, enough for bringing the entire cultivated land under irrigated production (water adequacy ratio > 1.0) and its full utilization also does not guarantee food self-sufficiency, unless it is complimented by sufficient amount of arable land. The dependence on food imports also increases for those water rich countries, with lower utilization of irrigation potential.

10. Too little of renewable water resources, when combined with too little of agricultural land under cultivation, can avert water crisis in some hot and hyper-arid countries by drastically reducing agricultural water demand, though there could be severe problems of food shortage.

11. In sum, the criteria for assessing the magnitude of food security and water management challenges have to factor in the role of agricultural land, particularly the cultivated land. When this is done: we have four different categories of countries emerging: 1] countries with large amount of renewable water and cultivated land having both water and food self-sufficiency; 2] countries having large amount of renewable water resources but also having disproportionately larger amount of cultivated land, resulting in low 'water-adequacy' but 'food surplus' though facing occasional water shortages; 3] countries having sufficient amount of

cultivated land but low water availability, facing different degrees of water shortages (with some experiencing groundwater mining problems) and food self-insufficiency, depending on the actual per capita cultivated land, water availability, and extent of its utilization for irrigation; and, 4] countries having high values of 'water adequacy' most of the time because of large amount of renewable water and low per capita cultivated land, and sometimes because of disproportionately lower amount of cultivated land combined with low water availability, but mostly dependent on food imports.

12. There are around 60 countries belonging to the fourth category, which have adequate amount of water in the natural system, which can be tapped to increase irrigation intensity, thereby reducing food imports. On the other hand, there are 20 water scarce countries belonging to the third category (mostly in Sub-Saharan Africa), with poor water adequacy for crop production, but also having varying quantities of water still remaining un-utilized and can be harnessed to increase irrigation.

13. The modelling of per capita milk production against the composite index of water-adequacy, cultivated land and pasture land shows that the index is a significant variable explaining the quantum of milk production in a country. The value of the composite index ranged from a lowest of 0.003 (Kuwait, Bahrain, United Arab Emirates, Sao Tome and Principe) to the highest of 4.275 (New Zealand). The composite index explained variation in per capita milk production to the extent of 61 per cent, in a linear fashion. However, two trend lines clearly emerge, one with steep slope and the other with mild slope. Most countries on the steep gradient line are developed countries experiencing cold and temperate climate. Most of the countries falling on the mild gradient line are the developing countries, under hot tropical climate. This differential productivity is mainly due to the difference in climate which changes the production potential of the land, dairy production technologies, and production practices.

    The countries which fall on the steeper gradient line, which we call the "technical efficiency frontier", generally have higher milk production efficiency. This can be due to the following facts: 1] favourable climatic conditions (high humidity, low temperature and higher incident solar energy) leading to production of higher biomass with lower transpiration resulting in higher crop/fodder/grass yields and higher physical productivity of water; 2] adoption of certain high yielding varieties of cows such as Holstein Friesian and Jersey, which are better suited to the cold and temperate climates[2]; and 3] high energy conversion ratios due to stock feeding of animals.

8 Conclusions and Policy

Historically, analysis of water scarcity problems and food security challenges facing nations around the world were assessed as a single challenge, using simplistic considerations of renewable water availability and extent of withdrawal of renewable (blue) water from the natural system. Problems of domestic food shortage facing certain countries were largely viewed as a water management challenge, meaning if more water is made available for irrigation, the agricultural situation would improve. It ignores the fact that limited availability of cultivable land renders most of the available (blue) water un-usable for agricultural production. Similarly, water management challenges of countries were largely viewed from the perspective of renewable water availability, suggesting that those having low renewable water availability in per capita terms would imminently face water scarcity. Conversely, moderately high renewable water availability in per capita terms was considered to an indication of 'water richness', without considering the per capita land under cultivation, which determines the demand for water for that sector. Such skewed analyses ignore the role of access to agricultural land, particularly cultivated land that increases the availability of green water for crop production in determining agricultural production potential of a country.

A related concern raised by many developed countries and environmental groups around the world is the excessively high withdrawal of water in developing countries from the natural system for crop production and other sectors of the water economy, leaving less water for ecological flows causing environmental water stress. To deal with the water scarcity problems and environmental water stress, suggestions are often made for tropical countries and regions withdrawing large amount of water (in per capita terms) for economic activities to reduce their agricultural water footprint by improving crop water productivity (Mekonnen and Hoekstra, 2014). In the same manner, suggestions are made to rich countries that maintain high calorie diet to reduce the consumption of food products that

2 Research in Rajasthan in western India shows that the milk yield was negatively correlated with and inter-calving period was positively correlated with maximum daily temperature, maximum humidity, and maximum temperature/humidity index and sunshine hours, for cross breeds of Holstein Friesian cows.

consume large amount of water per unit of calorie, to reduce their agricultural water footprint (Hoekstra and Chapagain, 2007; Jalava et al., 2014). While the former ignored the actual water withdrawal by countries for agricultural production, which also include withdrawal from soil profile (green water)--a component generally very low for tropical countries and very high for countries with cold and temperate climate--, the latter ignored the extent of food import by many of the countries maintaining high calorie dietary regime and its likely water and livelihood implications for the countries which actually export this food. Such prescriptions based on simplistic considerations of irrigation water withdrawal and water footprint analysis would be highly misleading.

First of all, our analyses suggest that water-rich countries, which have disproportionately lower amount of agricultural land than renewable water (in per capita terms), will have comparative advantage in maintaining ecological flows in the hydrological system as compared to those which are not so water-rich but have disproportionately larger amount of arable land. Analysis using global data sets on agricultural land use and outputs and the computed values of the two indices, viz., water-land index shows that the per capita virtual water export from/import into a country is well simulated by the 'water adequacy', and the amount of per capita cultivated land, rather than amount of renewable water resources of that country in per capita terms. Further, countries having high values of water-land index, and large amount of rich pasture land (in per capita terms) would be able to produce surplus milk, as indicated by the cases of New Zealand, Denmark, Netherlands, Germany and United Kingdom. This was suggested by the high correlation between composite index of 'water-cultivated land-pasture land' and the per capita annual milk production.

The countries having large amount of cultivated land per capita and sufficient water to cover the entire land under intensive production will have the comparative advantage for producing agricultural surplus for export. This is followed by countries having high 'per capita cultivated land', but relatively low 'water adequacy index' (40 in number). Countries that are very water-rich, but having very little amount of cultivated land in per capita terms (69 in number) will not face problems related to water supply, but might have to depend on food imports to meet domestic consumption needs. Nevertheless there are many countries under the second and third category (21 out of the 40 nos. and 60 out of the 69 nos., respectively), which can increase their production through increasing the utilization of irrigation water.

Changes in consumption pattern would help countries having high water footprint in their diet (especially the high income countries of Europe and the far-East) if the countries from which the food is imported face water scarcity and resource depletion. Also, some water scarce countries which leave high water footprint in agriculture by producing surplus and exporting, while maintaining diet with low water footprint, can reduce their water footprint by reducing agricultural commodity exports over a period of time, as their economic condition improves. Whereas some of the water-scarce countries, which maintain diet with high water footprint (rich countries) and also produce surplus need to first focus on changing their consumption patterns and then reducing exports. For this, the consumption patterns of the food importing countries need to change. If that doesn't happen, the major production base can be shifted to water rich countries which are also land rich, such as Argentina, Brazil and Canada.

Overall, there is a need to develop quantitative indicators for assessing water availability and food security situations of individual countries separately using the parameters that were found to have significant impact on water supply and overall water demand, as well as crop and dairy production potential. These parameters are: water adequacy ratio (which considers renewable water resources, cultivated land, climate and crop growing period); per capita cultivated land; and, pasture land index (including per capita pasture land and pasture land coefficient).

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