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ORIGINAL ARTICLE

Global evaluation of the effects of agriculture and water management adaptations on the water-stressed population

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Abstract Fresh water is one of the most important resources required for human existence, and ensuring its stable supply is a critical issue for sustainable development. The effects of a general set of agriculture and water management adaptations on the size of the world's water-stressed population were assessed for a specific but consistent scenario on socio-economic development and climate change during the 21st century. To maintain consistency with agricultural land use change, we developed a grid-based water supply–demand model integrated with an agro-land use model and evaluated the water-stressed population using a water withdrawals-to-availability ratio for river basins. Our evaluation shows that, if no adaptation options are implemented, the world's water-stressed population will increase from 1.8 billion in 2000 to about 3.3 billion in 2050, and then remain fairly constant. The population and economic growth rather than climate change will be dominant factors of this increase. Significant increase in the water-stressed population will occur in regions such as North Africa and the Middle East, India, Other South Asia, China and Southeast Asia. The key adaptation options differ by region, depending on dominant crops, increase in crop demand and so on. For instance, 'improvement of irrigation efficiency' and 'enhancement of reclamation water' seem to be one of important options to reduce the water stress in Southeast Asia, and North Africa and the Middle East, respectively. The worldwide implementation of adaptation options could decrease the water-stressed population by about 5 % and 7–17 %, relative to the scenario without adaptations, in 2050 and 2100, respectively.

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1 Introduction

Fresh water is one of the most important resources required for human existence, and ensuring its stable supply is a critical issue for sustainable development. At present, the annual water withdrawal due to human activity is less than 4 thousand $km^3 yr^{-1}$ and since this is less than 1/10 of the annual total for water availability (Oki and Kanae 2006) there may seem to be little need for anxiety about water shortages. However, since the geographical distribution of water resources and human populations is not homogeneous, it is estimated that approximately 1.3–2.3 billion people are living in water-stressed basins - with water stress defined on the basis of indices such as the annual withdrawals-to-availability ratio and per capita annual water availability (Vörösmarty et al. 2000; Alcamo et al. 2007; Hanasaki et al. 2008; Arnell 2004; Hayashi et al. 2010). There is, therefore, concern that any increase in water stress for populations may become a cause of conflict. According to a study carried out by Shiklomanov (1999), annual water withdrawals, worldwide, have increased about threefold during the latter half of the 20th century mainly due to an increase in agricultural water withdrawals associated with irrigated area expansions. In the 21st century, further increases in water withdrawals are expected as domestic and industrial water withdrawals continue to increase associated with population and economic growths, especially in developing regions (Alcamo et al. 2007). Decreasing water availability caused by climate change is also predicted for some regions such as the Mediterranean and part of America and Africa (IPCC 2007). Therefore, it is important to evaluate the availability of water resource on a regional basis, taking into account impacts due to both socio-economic and climatic changes. Interest in possible adaptations to climate change is increasing since many of these measures are expected to help alleviate global warming and bring about an improvement in living conditions (IPCC 2007). The importance of such adaptations has also been acknowledged in international policies. For instance, the Cancun agreements adopted in 2010 by the sixteenth session of the Conference of Parties (COP16) of the United Nations Framework Convention on Climate Change (UNFCCC) support the construction of a framework for adaptation and the enhancement of adaptive activities (UNFCCC 2010).

A number of studies have been performed to evaluate adaptations related to water management (IPCC 2007). Most of them examined adaptation in real water management systems for individual regions. As examples of the studies to ensure the long-term water supplies, Arnell and Delaney (2006) assessed adaptation processes and constraints affecting the public water supply in England and Wales, and pointed out that awareness of climate change and capacity building to deal with climate change are essential components of the adaptation process. De Bruin et al. (2009) ranked various adaptation options for water management in the Netherlands, based on stakeholder analysis and expert advice, and carried out a preliminary cost-benefit analysis. Tanaka et al. (2006) examined the ability of California's water supply to adapt to long-term climatic and demographic changes, and concluded that the water supply system appears physically capable of adapting to the expected climatic and demographic changes, albeit at significant cost. Although these studies are valuable tools in building up an understanding of the adaptations required for individual regions, they are insufficient to discuss strategies for the availability of water resource on a worldwide basis. One example of studies that have looked at all regions of the world is that of Kirshen (2007) which estimated the cost of implementing adaptations in response to water shortages, up to 2050, based on a set of assumptions regarding adaptations and cost functions. The total cost of adaptation was estimated at $531 billion by 2030, using the SRES (Special Report on Emissions Scenarios) A1B scenario (IPCC 2000), with about three quarters of this cost being required to implement changes in Asia and Africa. This estimation is interesting because it considers the worldwide implementation of a certain level of adaptation. However, in the Kirshen study, the amount of irrigation water withdrawal, which comprises the largest share of total water withdrawals (World Bank 2008) and will have a major effect on water use in the future, was estimated from a study by Fischer et al. (2007) for the socio-economic A2r scenario (Grübler et al. 2007), in which the assumptions made regarding agricultural land use and adaptations (e.g., irrigated sites, crop types, and planting times) are unclear.

In our study, the effects of a generic set of agriculture and water management adaptations on the water-stressed population, worldwide, are estimated without examining their cost, using the size of the water-stressed population. There is no doubt that a large water-stressed population puts pressure on the availability of the water resource and is likely prevent the sustainable development. In order to maintain consistency with agricultural land use change and to take into account adaptations for agriculture and water management implemented under a specific scenario incorporating socio-economic development and climatic change, we developed a water supply–demand model integrated with an agro-land use model. Then, we evaluated the effects of the adaptations on the global water-stressed population. In Section 2, the methodology of this study is described. It includes descriptions of the model used (Section 2.1), adaptations considered in this study (Section 2.2), socio-economic scenario (Section 2.3), simulation cases (Section 2.4), and climate change scenarios (Section 2.5). Results of water availability, water withdrawals, and water-stressed populations for each of the simulation cases are presented in Section 3. Finally, conclusions from our evaluations for the adaptations are provided in Section 4.

2 Methodology

The framework of the models used is shown in Fig. 1. The analysis procedure used is as follows. First, the amount of cropland required to meet the predicted food demand for a specific scenario on socio-economic development and climatic change is estimated by using the agro-land use model. Second, the annual water availability and the water withdrawal are estimated by using the water supply–demand model for the same scenario on socio-economic development and climatic change. For the evaluation of the irrigated water withdrawal, information on the irrigation grid, crop type, variety and planting times, which are obtained from the results of the agro-land use model, is used. The domestic water withdrawal is estimated considering population change and an increase in the per capita withdrawal associated with the economic growth. The industrial water withdrawal is estimated to keep consistency with the change of industrial activities under the socio-economic scenario; and to this end, the data on production volumes of water-intensive sectors and energy efficiency are obtained from the Dynamic New Earth 21 plus (DNE21+) model (Akimoto et al. 2010). The details of the estimation of water withdrawals and water availability are described in Sections 2.1.1–2.1.4. Finally, the population living in water-stressed river basins is evaluated using the ratio of annual water withdrawals to annual water availability. These calculations are carried out at every decade from 2000 to 2050, and at specific time points for 2070 and 2100.

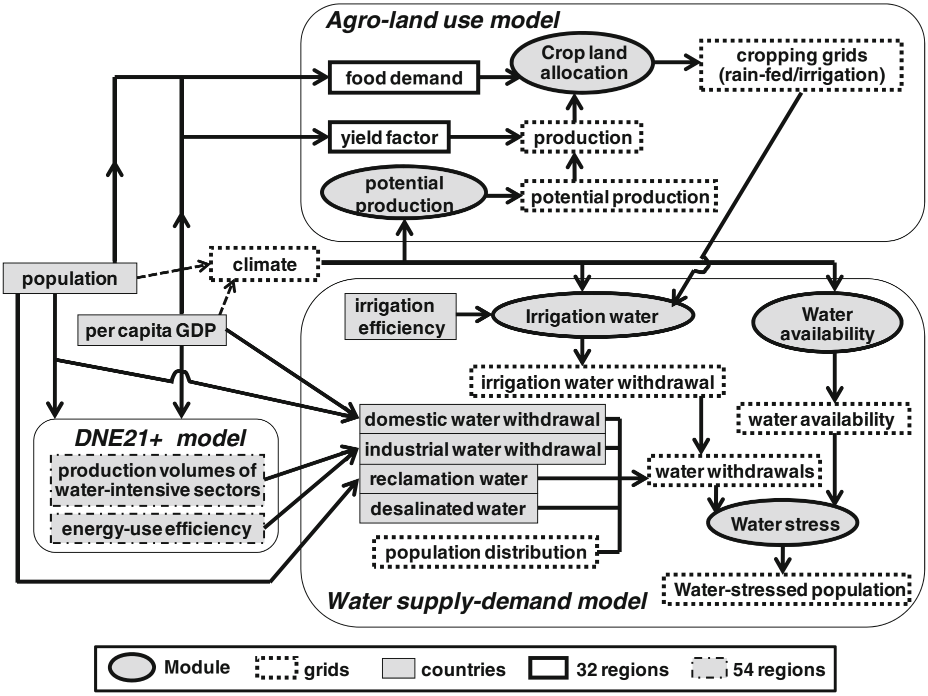


Fig. 1 Framework of the models. (For the countries included in each of the 32 regions and the 54 regions, refer to Kii et al. (2011) and Akimoto et al. (2010), respectively)

2.1 The water supply–demand models

2.1.1 Outline of the model

The water supply–demand model is a grid-based model with 15×15 min resolution, and consists of three modules (see Fig. 1). One is a 'water availability' module that calculates the annual water availability for river basins, based on annual runoff. The grid-based annual runoff is estimated from the data projected by AOGCMs (atmosphere-ocean coupled general circulation models) (PCMDI 2004). Therefore, the water availability in this study includes the surface runoff and renewable groundwater except for the fossil groundwater. Data for the river basins are derived from the Total Runoff Integrating Pathways (TRIP) database (Oki 2001).

The second module is the 'irrigation water' module in which water withdrawal for irrigation is estimated, based on the net irrigation requirement and irrigation efficiency- expressed as the ratio of net irrigation requirements relative to irrigation water withdrawals. The net irrigation requirement is estimated as the difference between potential evapotranspiration and actual evapotranspiration during the growing period for each crop planted in an irrigation grid. The potential and actual evapotranspiration values are calculated using the Penman-Monteith method and the water-balance method employed in the Global Agro-Ecological Zones (GAEZ) model (Fischer et al. 2002). Information on the irrigation grid, crop type, variety and planting times are obtained from the results using the agro-land use model. In this study, a partially revised agro-land use model from the original model (Kii et al. 2011) was used. The outline of the revised agro-land use model is presented in Appendix 1. The current level of irrigation efficiency used in each of regions examined is based on a study carried out by Döll and Siebert (2002), as shown in Table 1. Figure 2 shows a comparison between our estimation and the results obtained by Siebert and Döll (2010) for irrigated area and net irrigation requirement. It can be seen that our estimation agrees fairly well with the results of Siebert and Döll (2010), except for Oceania. This difference for Oceania may be caused by the simplification in our model, that is, the share of land available for irrigation in each of the grids is assumed to be either 0 or 100 %; and sophistication of the assumption for the share in each grid may be necessary. However, the irrigated area in this region is small (i.e., less than 1 % of the world irrigated area); therefore it is thought that this discrepancy is not likely to cause significant problems in this study.

The third module used is the 'water stress' module, in which the ratio (R) of annual withdrawal relative to annual water availability, as expressed by Eq. 1, is calculated for each of the river basins:

$$R = (domes + indus + irri - recla - desali)/WA \tag{1}$$

where *domes*, *indus* and *irri* stand for domestic, industrial and irrigation water withdrawals, respectively, and *recla*, *desali* and *WA* stand for reclamation water, desalinated water and water availability, respectively. The amounts of *WA* and *irri* are obtained by the calculations using the first and second modules, and those of *domes*, *indus*, *recla* and *desali* are estimated

Table 1 Current irrigation efficiency

18 regions	32 regions[a]	Efficiency[b]
U.S.	(United States)	0.60
Canada	(Canada)	0.70
Central America	(Mexico)	0.45
Brazil	(Brazil)	0.45
Other South America	(Paraguay, Uruguay, Argentina), (Other South America)	0.45
Western Europe	(Western Europe)	0.55
Eastern Europe, other FSU	(Annex I of FUSSR), (Other FUSSR), (Eastern Europe)	0.50
Russia	(Russia)	0.60
North Africa, Middle East	(Arabian Peninsula), (Upper Middle East), (Turkey), (North Africa)	0.60
Southeast Africa	(South East Africa)	0.55
Southwest Africa	(South Africa), (Other S. S. Africa)	0.55
Japan	(Japan)	0.35
China	(China)	0.35
Other East Asia	(Mongolia, DPRK), (South Korea)	0.35
Southeast Asia	(Cambodia, Laos, Vietnam), (Malaysia, Singapore, Brunei), (Indonesia), (Thailand), (Philippines)	0.35
India	(India)	0.55
Other South Asia	(Afghanistan, Pakistan), (Other Asia), (Iran)	0.55
Oceania	(Oceania)	0.70

[a] Corresponding to the 32 regions included in the agro-land model. For details of the countries included in each of the 32 regions, refer to Kii et al. (2011)

[b] This is assumed to be 0.1 lower for rice

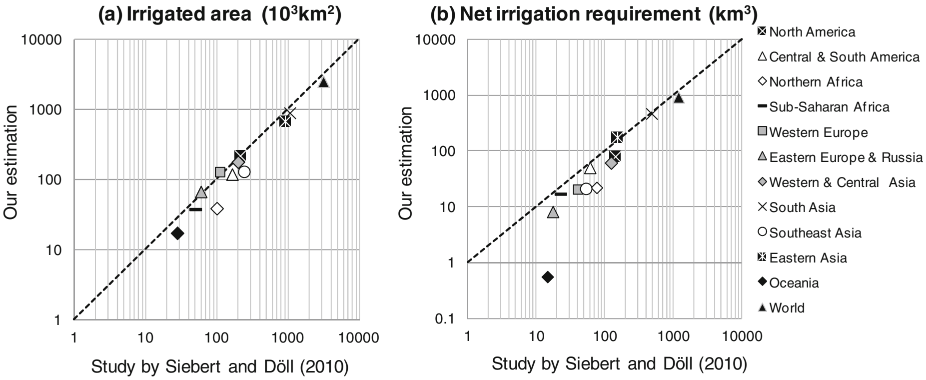


Fig. 2 Comparison between the estimation of this study and that of Siebert and Döll (2010) for (**a**) irrigated area and (**b**) net irrigation requirement. (The dotted lines are 1:1 lines)

maintaining consistency with the socio-economic scenario, as described in Sections 2.1.2–2.1.5. The numerator in Eq. 1 expresses the total withdrawal and shows that the withdrawal amount can be reduced by the use of reclamation water and desalinated water. The water withdrawal value for livestock is assumed to be much smaller than the sum of the domestic, industry and irrigation withdrawals and, in practice, can be assumed to be negligible by comparison. The number of people living in water-stressed basins is estimated using a criterion: 0.4 ≤ the withdrawal-to-availability ratio (Raskin et al. 1997). This indicator may not be perfect, but have been widely used (IPCC 2007). We adopted this indicator to evaluate long-term effects due to socio-economic development and climate change on water stress throughout this century. In the future, evaluations of possible impacts due to heavy rain and drought, and water deficiency on monthly or daily basis will be wanted.

2.1.2 Domestic water withdrawal

Domestic water withdrawal is estimated separately for urban and rural areas in each country, because that there are measurable differences in water withdrawal per 'access-person' between urban and rural areas especially in developing countries (Rosegrant et al. 2002). (The 'access-person' means people who are able to access safe water.) The water withdrawal per access-person for each of urban and rural areas in the future is calculated by using the functions of per capita GDP, which is described in Appendix 2 and can represent increases in the water withdrawal per access-person associated with the economic growth.

The urban and rural population scenario used is described in Section 2.3. The ratio of access-persons relative to the total population (hereinafter referred to as the 'AP ratio') for developed countries has already reached around 100 % in both urban and rural areas. The scenario for the AP ratios in developing countries is developed based on annual change rates from 1990–2004 (World Bank 2008) and three different target levels. The first of these is "Target 3 of Goal 7" of the Millennium Development Goals (MDGs) set by the UN (2000): "by 2015, halve the proportion of the population without sustainable access to improved drinking water, compared to 1990". The second and third targets assumed by us are even higher and follow on from these MDGs (i.e., reduce the proportion to one-quarter by 2050 and to one-eighth by 2070, compared to 1990). The resultant scenario represents the AP ratios in developing countries improving to 66–100 % by 2050 and to 92–100 % by 2100 from a point of 32–100 % in 2000 (for urban areas), and increasing to 52–100 % by 2050 and to 67–100 % by 2100 from a point of 12–100 % in 2000 (for rural areas).

2.1.3 Industrial water withdrawal

Industrial water withdrawal comprises two main components: manufacturing use and electric power plant cooling (FAO 2009). However, distinguishing between these two components at the global level is not common practice yet and, in a study carried out by Alcamo et al. (2007), total electricity production was used as a proxy for driving forces of water requirements for manufacturing and electric power plant cooling. Because three quarters of final energy consumption in the manufacturing sector depends on non-electricity energy (IEA 2010), total electricity production does not accurately reflect water requirements for the manufacturing activities. Furthermore, fresh water demand for electric power plant cooling depends largely on the plant type and plant location (e.g., hydro- and wind-power plants do not need water for cooling, and seawater can be utilized for cooling in onshore thermal and nuclear power plants.) Therefore, total electricity production is not always an adequate expression of fresh water requirements for electric power plant cooling.

In the water supply–demand model, industrial water withdrawal (*indus*) estimates are based on changes in industrial water requirements (*Req*) and the water-use efficiency (*Ef*) for each country, as shown by Eq. 2:

$$indus_t = indus_{2000} \times (\mathrm{Re}q_t/\mathrm{Re}q_{2000}) \times (Ef_t/Ef_{2000}) \tag{2}$$

where the subscript t indicates the year. The value of $indus_{2000}$ is obtained from the FAO database (FAO 2009). An important assumption is that the *Req* is expressed by a weighted sum of production volumes (hereinafter referred to as 'weighted production') for manufacturing sectors with large shares of industrial water withdrawal (i.e., iron and steel, the chemical industry, and pulp and paper sectors (Matsuoka and Takahashi 2003; METI 2007)). The production volume for each of these sectors is expressed by the volume of the representative product involved (i.e., crude steel, ethylene, propylene and ammonia and paper, respectively) and the relevant data can be obtained from the database for the DNE21+ model (Akimoto et al. 2010). The weightings used for industrial water withdrawal per unit of production volume for these representative products are 1.0, 0.7, 0.8 and 8.7 for crude steel, ethylene and propylene, ammonia and paper, respectively (RITE 2010). Although this set of weightings is taken from an estimate prepared for Japan in 2002, for simplicity's sake it is applied to all the countries since there is a high level of correlation (0.91) for the year 2000 between industrial water withdrawal (based on FAO data (2009)) and the weighted production for the major countries studied (RITE 2010).

The energy-use efficiency for the production of crude steel by blast furnaces is used as a proxy for water-use efficiency since there was a high level of correlation (0.73) between water withdrawal and energy use for crude steel produced in this manner from 1962–2002 in Japan (RITE 2010). Another reason for estimating the water-use efficiency in this way is that there is so little historical data available to estimate reliable trends for improved water-use efficiency in other sectors. It is assumed that the improvement of water-use efficiency in the iron and steel sector, which has the largest share of industrial water withdrawals for any manufacturing sector, also reflects improvements in other sectors. Predicted energy-use efficiency data, up to the year 2050, have been obtained from the DNE21+ model and, from 2050 on, estimates are extrapolated based on the assumption that the improvement rate will gradually decrease.

The scenario developed in this study for the weighted production indicates that the largest increases can be expected in developing countries, compared to the developed countries (for instance, the estimated annual change rate of weighted production for 2000–2050 is expected to range from −0.5 to 1.7 % p.a. for developed countries, and from −0.5 to 5.1 % p.a. for developing countries.) The scenario for the energy-use efficiency used in this study indicates that efficiency improvements in developing countries will be slightly larger than those in developed countries (i.e., a regional mean annual improvement rate for efficiency during 2000–2050 of 0.59 % and 0.63 % p.a. for developed countries and developing countries, respectively). The values of the weighted production and the energy-use efficiency for representative regions are presented in Appendix 3.

2.1.4 Reclamation water and desalinated water

According to the definition provided by the FAO (2009), reclamation water is treated domestic and industrial wastewater which meets all applicable environmental standards (although these standards may differ from country to country). Since available information on reclamation water is limited (i.e., data are available for only about 30 countries around the world for the 1990s and 2000s (FAO 2009)), in this study we assume that reclamation water is introduced only in urban areas, and that its use will increase as the urban population expands.

The use of desalinated water is limited, compared with reclamation water, because of issues regarding cost and location. As a result, it is estimated that only 7 km^3 yr^{-1} of desalinated water were utilized in parts of the Middle East and the U.S. in 2010, based on FAO statistics for 2000 (FAO 2009), although some other countries are considering its adoption (Tamura 2009). In this study, it is assumed that future desalinated water use will be negligible for most countries. For some countries, in which desalinated water is already in regular use, it is assumed that the level of use will remain the same as that in 2010. The possible expansion of desalinated water use will be considered in a future study.

2.1.5 Grid-based distribution of domestic and industrial water withdrawal, reclamation water and desalinated water

Domestic water withdrawals estimated on a country-wide basis for urban and rural areas are distributed in proportion to the population in each grid. The scenario used for the distribution of population and urban areas is described in Appendix 5. Industrial water withdrawal, reclamation water and desalinated water are distributed across each grid in the same manner, but it is assumed that industrial water withdrawal, reclamation water and desalinated water are used solely in urban areas.

2.2 Adaptations

According to the IPCC's reports (IPCC 2007, 2001), there are some adaptation options for water supply and demand, which are applicable to a range of systems. Examples of the supply-side adaptation options are increasing storage capacity by building reservoirs and dams, extraction of ground water, desalination of sea water, and water transfer; and those for the demand-side adaptation options are enhancement of reused water, reduction in water demand for irrigation by changing cropping calendar, crop varieties, and irrigation method and area planted, reduction in water demand for irrigation by importing agricultural water (i.e. virtual water), and expanded use of economic incentives. It is also pointed out that each option has both advantages and disadvantages; and that the benefits of the options depend on local circumstances. For instance, increases in storage capacity or abstraction from water courses tend to have adverse environmental consequences; desalination uses a large amount of energy and may be inharmonious with mitigation of global warming; and pumping large volumes of ground water may lead to a depletion of fossil water. Virtual water import is an adaptation option for some regions such as North Africa and the Middle East; however, other factors such as high costs of farm laborer and lands rather than the water shortage seem to predominate as the cause of the large amount of virtual water import in regions such as Japan, who import the third largest amount of virtual water in the world (Chapagain and Hoekstra 2004) in spite of little water-stress.

In this study, considering the feasibility of the adaptation options in most of regions of the world, we have selected following three adaptation options; (i) changing varieties and planting times, (ii) improvement of irrigation efficiency, and (iii) enhancement of reclamation water. We assume that they will be available everywhere from 2020 onwards. The other assumptions for each of the adaptation options are as follows:

(i) Changing varieties and planting times

The varieties and planting times selected for the crops found in each grid are those which yield the maximum production potential under specific climate regimes considered.

(ii) Improvement of irrigation efficiency

It is assumed that, in water-stressed river basins, irrigation efficiency can be improved by 5 % in terms of the difference between an ideal maximum (=1) and the efficiency of the previous analysis year (e.g., the irrigation efficiency in 2030 can be increased by (1 – the efficiency in 2020) x 0.05, compared to 2020). This means that the potential for the further improvement is relatively large where the current level of the efficiency is low. The value of "0.05" was adopted so that the range of the efficiencies were comparable in magnitude to values utilized in studies by Alcamo et al. (2007) and Fischer et al. (2007), although the high uncertainty of potential changes in irrigation efficiency was mentioned in their reports. Based on this assumption, the irrigation efficiency of a river basin which currently has the highest efficiency (0.7) can be improved to 0.76 and 0.78 by 2050 and 2100, respectively, and that a basin with the lowest efficiency (0.35) can be improved to 0.47 and 0.52 by 2050 and 2100, respectively.

(iii) Enhancement of reclamation water

If a basin is still under water stress even after the irrigation efficiency is improved, the amount of per capita reclamation water in urban areas is enhanced by 20 %, compared to the previous analysis year. This increase ratio is based on the largest value observed during 1990–2000 in those countries where FAO statistics on reclamation water are available (i.e., it is assumed the amount of per capita reclamation water in urban areas had increased from about 8 m^3/yr to 10 m^3/yr during this period in Yemen). For countries in which reclamation water has not been utilized in the previous analysis year, the value is set at 20 % of the per capita domestic water withdrawal figure for urban areas. This estimate of newly introduced reclamation water is uncertain and we have it by reference to the ratio of reclamation water relative to domestic water withdrawal, worldwide, in 2000 (i.e., reclamation water and domestic water withdrawal totals for urban areas, worldwide, of 35 km^3 yr^{-1} and 260 km^3 yr^{-1}, respectively). Naturally, the estimated reclamation water value cannot exceed the total amount of domestic and industrial water withdrawals from urban areas.

We consider that the levels we have adopted for the various adaptation options are close to the maximum levels that can be expected in practice.

For those cases in which adaptations are not implemented, it is assumed that the crop varieties and planting times used in future years will be the same as those yielding maximum production potential under the climate in 2010, and that the irrigation efficiency of each of the countries will be maintained at the current level. It is assumed that the per capita reclamation water values for urban areas will also remain at 2010 levels. These levels are assumed to be at the low end of the range so that potential effects due to the implementation of adaptation options can be readily evaluated, although they may not always be very practical.

2.3 Socio-economic scenario and food demand

The scenario on GDP and population is adopted from the ALPS-A scenario which is one of scenarios developed considering the historical trend of socio-economic changes (Akimoto et al. 2011). In the scenario, it is predicted that the global average for per capita GDP will increase from US$5,230 in 2000 to US$12,350 and US$24,400 by 2050 and 2100, respectively, and that the world's population will increase from 6.1 billion in 2000 to approximately 9.1 and 9.3 billion by 2050 and 2100, respectively (The country-level scenarios for GDP and population have been released in RITE (2011b).). Future urban population for each country is estimated based on the total population mentioned above and the urban population ratio relative to the total population. The ratio is projected by using a function of per area GDP (see Appendix 4), and the resultant scenario represents that the urban population ratio in the world will increase from 0.46 in 2000 (UN 2009) to 0.63 and 0.70 in 2050 and 2100, respectively. As shown in Fig. 3, significant increases in total population are projected throughout the 21st century for Africa, the Middle East, and South Asia except for India. In China, India and Southeast Asia, population growth is projected to peak around the middle of this century. As a similar trend of the population scenario in these regions, it is presented that the growth of urban population will be much larger than that of rural population. For other regions, it is assumed that the total population growth will be small or negative, and that urban population will continuously account for the most of total population.

Grid-based distributions of population and urban areas in the future are estimated based on population maps for the year 2000 developed by PBL (2009) by assuming the concentration of population to urban areas and the spread to the areas located in close to proximity (see Appendix 5).

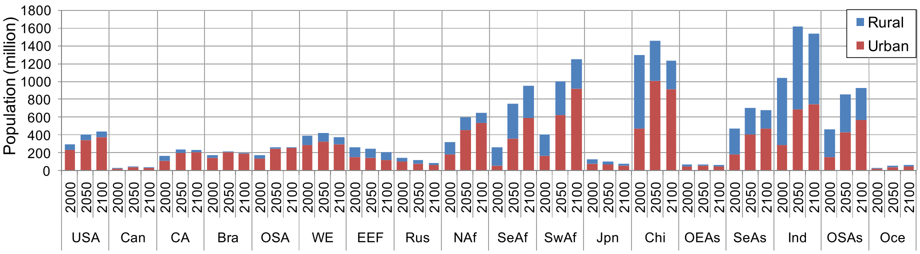


Fig. 3 Population scenario. (In this figure, all the countries of the world are aggregated into 18 separate regions; *USA* U.S., *Can* Canada, *CA* Central America, *Bra* Brazil, *OSA* Other South America, *WE* Western Europe, *EEF* Eastern Europe and other FSU, *Rus* Russia, *NAf* North Africa and Middle East, *SeAf* Southeast Africa, *SwAf* Southwest Africa, *Jpn* Japan, *Chi* China, *OEAs* Other East Asia, *SeAs* Southeast Asia, *Ind* India, *OSAs* Other South Asia, Oce Oceania)

The dietary energy demand has been estimated for all 32 regions, taking into account the increase in per capita dietary energy demand associated with economic growth. The world total for estimated dietary energy demand is set at 16800, 26400 and 27400 ($x10^{12}$ cal day^{-1}) for 2000, 2050 and 2100, respectively. This dietary energy demand is converted into the weight demand for eight specific crops adopted in the agro-land use model, namely, *Triticum*, *Oryza*, *Zea mays*, *Saccharum*, *Glycine max*, *Elaeis* and *Brassica napus* (hereinafter referred to as wheat, rice, maize, sugar cane, soybeans, oil palm fruit, rapeseed, respectively), and others. (For the scenario of food demand, refer to Appendix 6.)

2.4 Simulation cases

Three different simulation cases are examined in this study. One is the 'reference case' in which none of the adaptations mentioned in Section 2.2 are implemented, despite climate change. The second case examined is the 'adaptation case' in which the three kinds of adaptation mentioned previously are all implemented from 2020 onwards and climate change takes place in the same manner as in the reference case. The third case examined is the 'fixed climate case' in which the climate is assumed to remain at the 2010 level and no adaptation options are implemented. This last case is included in order to allow the impacts of socio-economic change to be evaluated separately from the impacts of climate change.

2.5 Climate change scenarios

The global mean temperature (GMT) for the reference case was calculated by using MAGICC ver. 5.3 (Wigley 2008) with an equilibrium climate sensitivity of 3 °C. In the near future, we expect to be able to develop greenhouse gas (GHG) emission scenarios that are compatible with the newly developed socio-economic scenario. However, as scenarios for all the GHGs have not yet been developed, the emission scenarios for SRES-A1v2-MiniCAM (IPCC 2000) are utilized as substitutes, since the scenario for CO_2 emission from industry which was examined for the newly developed socio-economic scenario (RITE 2011a) agrees fairly well with that of SRES-A1v2-MiniCAM. The calculated GMT rise, relative to 1990, is expected to be 0.9 °C by 2030, 1.6 °C by 2050 and 3.7 °C by 2100.

Grid-based climate data for temperature, precipitation, wind speed, runoff etc. are based on a pattern-scaling method (for details, refer to Appendix A1 of Hayashi et al. (2010)), integrating data for the GMT rise and climate change patterns. Projections generated for the SRES A1B scenario by two AOGCMs, MIROC3.2 (Medres) (Hasumi and Emori 2004) and CGCM3.1(T63) (Canadian Centre for Climate Modeling and Analysis 2010) were obtained from the PCMD database (PCMDI 2004) and used to produce data on climate change patterns. These patterns were then used to consider the differences in climate change projections caused by the AOGCMs, although further estimations based on a larger number of AOGCMs remain to be addressed in the future research to improve understanding of the effects of inter-AOGCM differences. Before integration with the GMT, the data on all climate change patterns (except for runoff) were adjusted to match the climate data observed from 1961–1990 (IPCC 2008; Tyndall Center 2003), although only runoff data was adjusted in the GSWP2 simulations for the period from 1986–1995 (Institute of Industrial Science Tokyo University 2004).

3 Results

3.1 Water availability and water withdrawals

3.1.1 Water availability

The estimated world total of annual water availability in 2000 and 2010 is 45 thousand km^3 yr^{-1}. Global warming is expected to gradually increase the world total for water availability, and the estimated amount for the reference and adaptation cases is 45–46, 46–47, and 49–51 thousand km^3 yr^{-1} in 2030, 2050 and 2100, respectively. (The ranges for 2050 and 2100 show differences in the amount of runoff between MIROC data and CGCM data.) The impact of global warming is different among regions. The annual water availability in some regions such as Central and south America, Philippine and Thailand is expected to decrease, while that in other regions such as China, India, southeast Africa, Russia and Canada is expected to increase due to global warming. In this study, it is assumed that the increased runoff associated with global warming will be fully available for use. However, the possible impacts of heavy rain and drought on annual water availability are still to be considered.

3.1.2 Domestic and industrial water withdrawal

Figure 4 shows estimated domestic water withdrawals for urban and rural areas up to 2100. Significant increases are predicted for urban withdrawals in regions such as Middle East, Africa, Southeast Asia and South Asia. In rural areas, the predicted increase in withdrawals is relatively small, because that the population growth in rural areas will be very small or negative, compared to urban growth. The estimated world total for combined urban and rural domestic water withdrawals is expected to become 2.3 times larger than the 2000 level by 2050, and 2.6 times larger by 2100. The major reason for this growth is the significant increase in urban withdrawals in some regions, as mentioned above.

The world total of industrial water withdrawal is expected to increase to 1.8 times the 2000 level by 2050 and to have doubled by 2100. As shown in Fig. 5, a significant increase is estimated for Southeast Asia and South Asia because the increase in industrial water requirements associated with an enhancement of industrial activities are expected to exceed improvements in water-use efficiency. In North America, a moderate decrease in industrial

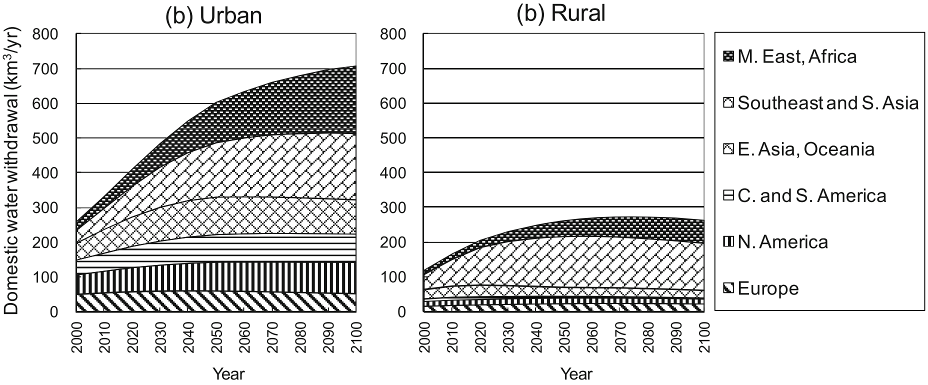
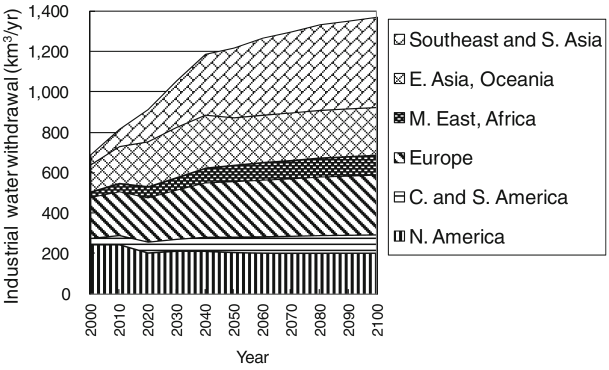


Fig. 4 Domestic water withdrawal for (**a**) urban and for (**b**) rural areas

Fig. 5 Industrial water withdrawal



water withdrawal is expected since any improvement in water-use efficiency is likely to be larger than the increase in industrial water requirements.

3.1.3 Agro-land use and irrigation water withdrawal

Table 2 shows the estimated land area required for crop production (including both rain-fed and irrigated areas) throughout the world in 2000 and 2010, and the annual change rates, up to 2100, for the reference case. The annual change rates for production volume and land productivity are also listed. Our estimation shows that the land area required to meet worldwide food demand is approximately 11.5 million km^2 in 2000. This is smaller than the arable land area shown on the map produced by Fischer et al. (2008) which estimated 15.5 million km^2, because fallow land is not included in our study. The required land area, worldwide, is expected to increase to 13.7 million km^2 by the year 2050 since the growth rate of the production volume demand is larger than that of land productivity. After 2050, it

Table 2 Required land area for crop production in 2000 and 2010, and annual rates of change for the required land area, the production volume and the land productivity from 2010–2050, and from 2050–2100 in the reference case. Only values for the world as a whole and for major regions are presented. (MIROC data are utilized for climate change patterns. The result estimated using CGCM data is not shown since the trend for required land area, worldwide, is similar to that produced using MIROC data)

	Required land area (10^3 km^2)		Rate of change from 2010–2050 (% p.a.)			Rate of change from 2050–2100 (% p.a.)		
	in 2000	in 2010	Required land area	Production volume[a]	Land productivity[b]	Required land area	Production volume[a]	Land productivity[b]
World	11,490	11,830	0.4	0.8	0.4	−0.2	0.1	0.3
Southwest Africa	1,420	1,765	1.2	1.3	0.1	−0.2	0.3	0.5
Southeast Africa	600	878	0.8	2.4	1.6	0.1	0.6	0.5
India	1,360	1,618	−0.9	0.6	1.5	−0.8	−0.1	0.7
China	1,350	1,518	−1.2	0.3	1.4	−0.9	−0.3	0.6

[a] Sum of production volumes for eight separate crops

[b] Estimated by dividing the sum of production volumes for eight separate crops by the required land area

is then expected to gradually decrease as the increase in production volume demand slows. Different regions also show different trends. For instance, in Southwest and Southeast Africa, the required land area is expected to keep increasing up to 2050 and then gradually decrease in the last half of this century. In China and India, which account for about half of the world's irrigated areas, the estimated growth rates for land productivity are larger than those for production volume after 2010. The required land area is then expected to continually decrease up to 2100.

Table 3 shows the estimated irrigated area and its annual rate of change in the reference case. In 2000, the total irrigated area, worldwide, was estimated to be 2.2 million km^2 with approximately 65 % of this area located in Asia. After 2010, the total irrigated area is expected to decrease because the irrigated area in regions such as China and India will be reduced along with a decrease in the required land area (as shown in Table 2). In Southwest and Southeast Africa, a large increase in irrigated area is not predicted although the required land area is expected to increase. This is because the amount of land available for irrigation is expected to remain at the same level as 2000, as mentioned in Appendix 1.

Figure 6 illustrates (a) irrigated area and (b) irrigation water withdrawal results for the reference case. This figure shows that irrigation water withdrawal is expected to decrease along with a decrease in the irrigated area. More than half of the irrigation water withdrawal is expected to be utilized for rice production, while the irrigated area for rice production accounts for only about 30 % of the total irrigated area. This means that the amount of water

Table 3 Irrigated area in 2000 and 2010 and the annual rate of change from 2010–2050 and from 2050–2100, in the reference case

	Irrigated area (10^3 km^2)		Rate of change from 2010–2050 (% p.a.)		Rate of change from 2050–2100 (% p.a.)	
	in 2000	in 2010	MIROC	CGCM	MIROC	CGCM
World	2,218	2,187	-0.2	-0.2	-0.2	-0.2
U.S.	211	216	0.1	0.1	0.0	0.0
Canada	8	8	0.0	0.0	0.0	0.0
Central America	45	49	-0.2	-0.1	-0.2	-0.2
Brazil	10	10	0.5	0.2	0.0	-1.0
Other South America	64	54	-0.3	-0.2	-0.4	0.1
Western Europe	129	128	0.1	0.1	0.0	0.0
E. Europe, other FSU	123	116	-0.5	-0.2	-0.4	-0.4
Russia	18	14	-0.3	-0.2	-0.3	-0.1
N. Africa and Middle East	143	123	0.3	0.3	-0.1	-0.2
Southeast Africa	26	34	-0.5	0.1	0.0	0.0
Southwest Africa	10	13	1.0	1.0	0.1	0.1
Japan	26	26	-1.3	-1.0	-0.5	-0.3
China	488	489	-0.8	-1.2	-0.4	-0.7
Other East Asia	19	17	-0.4	-0.4	-0.9	-0.6
Southeast Asia	112	113	-0.1	-0.1	-0.3	-0.2
India	537	548	-0.2	-0.2	-0.2	-0.2
Other South Asia	230	210	0.4	0.4	-0.2	-0.2
Oceania	17	18	0.1	0.2	0.0	-0.1

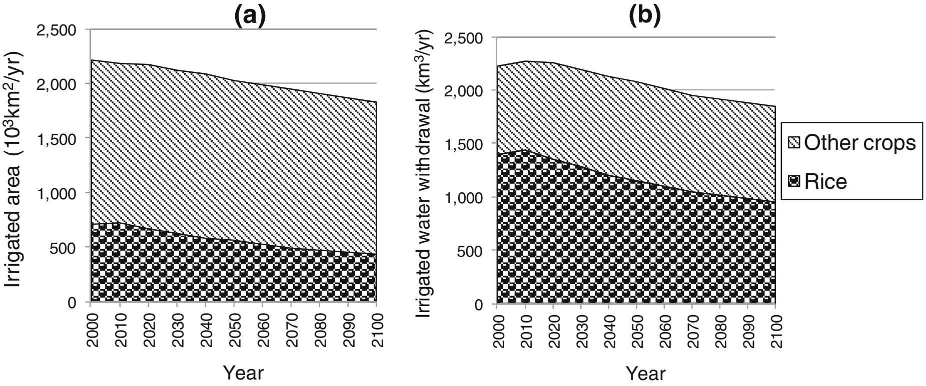


Fig. 6 (**a**) Irrigated area and (**b**) irrigation water withdrawal, worldwide, for the reference case (based on MIROC data for climate change patterns)

required for rice production is especially large and that any change in the irrigated land area for rice production has a significant effect on the irrigation water withdrawal amount.

For the fixed climate case, estimations of the irrigation water withdrawals show smaller values by about 2–7 % and 11–14 %, relative to the reference case in 2050 and 2100, respectively. For the adaptation case, the irrigation water withdrawals is expected to be reduced by about 19–22 % and 29–30 %, relative to the reference case in 2050 and 2100, respectively. These results suggest that the increase in the demand of the irrigation water withdrawals due to global warming is expected to be adequately alleviated by improvement of irrigation efficiency.

3.1.4 Summary of water withdrawals

Figure 7 shows the world mean of per capita water-withdrawal for the reference case. The estimations by Alcamo et al. (2007) for SRES-B2 scenario (IPCC 2000) are also presented. Similarities and differences between our study and theirs are as follows: per capita agricultural water withdrawal is expected to gradually decrease associated with a decrease in irrigated area or improvement of irrigation efficiency in both of these studies; the per capita industrial water withdrawal is expected to increase in our study, while it is expected to decrease in their study; the per capita domestic water withdrawal estimated by us is lower than their estimation by 73 m^3/year in 2050s; it results in our lower estimation of per capita total water withdrawal; and the reclamation water and desalinated water less contribute to total water withdrawal in terms of the world mean, although the amounts are not explicitly reported in their study. The difference in the per capita domestic water withdrawal may be caused by that water demand between urban and rural areas are separately estimated in our study, while it was taken as country-mean in their study. Further detailed study on the domestic water use in urban and rural areas will be required in the future.

Table 4 summarizes the estimated water withdrawals for the three simulation cases in this study. The values of domestic and industrial water withdrawals, and the desalinated water are shared among all of the simulation cases. The total of withdrawals in the world are expected to increase from 3,260 km^3 yr^{-1} in 2000 to 4,090 km^3 yr^{-1} in 2050 and 4,120 km^3 yr^{-1} in 2100. The remarkable decrease irrigated water withdrawal is expected in

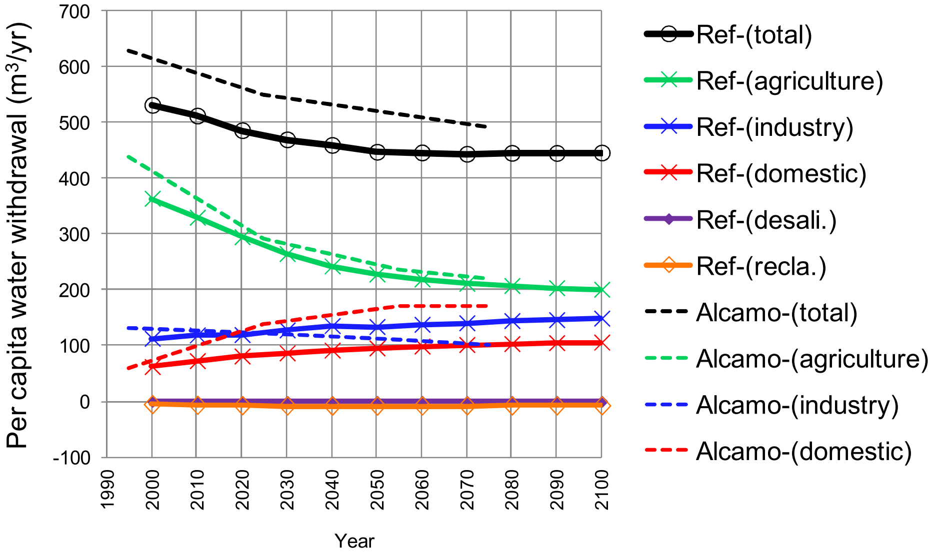


Fig. 7 The world mean of per capita water-withdrawal for the reference case

China and India associated with decrease in the irrigated area. In the climate fixed case, the irrigation water withdrawal of the world total, is expected to be reduced by 7 % in 2050 and 14 % in 2100 relative to the reference case owing to the alleviation of the impacts due to global warming. In the adaptation case, the total water withdrawal is estimated to be lower than that in the climate fixed case, in regions such as China, India, North Africa and the Middle East, Central America owing to reductions in the irrigated water withdrawals and enhanced reclamation. This result means that the adaptations adopted in this study have the potential to adequately alleviate the increase in the water withdrawals caused by global warming.

3.2 Effects of adaptations on the size of the water-stressed population

Projections of the world population under water stress are presented for the three simulation cases examined in Fig. 8. In the reference case, it is estimated that the water-stressed population will increase from 1.8 billion in 2000 to approximately 3.3 billion in 2050, and that it will remain more or less constant after 2050. The increasing tendency by about 2050 agrees with earlier studies (Alcamo et al. 2007; Oki and Kanae 2006), although the results for the latter half of this century varies among studies depending on assumptions on population and economic growths, distribution of population, climate change, etc. Based on the evaluation by using the annual water withdrawal-to-availability ratio, global warming is expected to make relatively little contribution to the size of the world total of water-stressed population, since the estimate for the fixed climate case is not very different from that for the reference case. This suggests that, even if the climate can be maintained at the current level through significant reductions in GHG emissions, water-stress effects may still not be greatly alleviated. A noteworthy result is that the water-stressed population, world-wide, is expected to be reduced by 2–5 % due to full implementation of the adaptation options considered, relative to the reference case, in 2050 and by 7–10 % in 2100.

Table 4 Summary of water withdrawals for the each of the simulation cases. Unit: km^3 yr^{-1}. Only values for the world as a whole and for major regions are presented

	Reference case						Climate fixed case[c]		Adaptation case		
	Domestic[b]	Industry[b]	Irrigation[d]	Reclamation	Desalination[b]	Total[a]	Irrigation[d]	Total[a]	Irrigation[d]	Reclamation	Total[a]
World											
2000	379	690	2,229	35	5	3,258	2,229	3,258	2,229	35	3,258
2030	717	1,057	2,196	68	7	3,897	2,141	3,842	1,937	104	3,600
2050	867	1,220	2,083	76	7	4,088	1,947	3,952	1,617	154	3,543
2100	974	1,374	1,851	73	7	4,120	1,585	3,853	1,312	198	3,455
China											
2000	47	111	647	23	0	782	647	782	647	23	782
2030	99	228	609	47	0	889	587	867	480	56	751
2050	105	216	481	51	0	751	476	746	297	76	542
2100	95	219	277	47	0	545	359	627	165	85	395
India											
2000	48	35	747	0	0	830	747	830	747	0	830
2030	162	190	697	0	0	1,049	685	1,037	632	13	972
2050	196	280	615	0	0	1,090	624	1,100	503	22	957
2100	199	357	523	0	0	1,078	442	997	351	33	874
N. Africa and the Middle East											
2000	24	20	125	5	2	161	125	161	125	5	161
2030	47	48	106	10	4	188	107	189	104	15	180
2050	62	62	144	12	4	253	114	223	124	24	221
2100	72	74	130	13	4	259	95	224	111	35	219
Southwest Africa											
2000	8	3	15	3	0	23	15	23	15	3	23
2030	28	6	21	5	0	51	24	53	21	5	51
2050	53	9	32	5	0	89	29	86	31	5	88
2100	99	12	29	6	0	134	26	131	31	7	135
U.S.											
2000	61	213	135	0	1	408	135	408	135	0	408
2030	78	187	155	0	1	420	146	410	149	5	409
2050	86	174	180	0	1	439	147	406	166	8	417
2100	92	166	213	0	1	470	140	398	174	12	419
Central America											
2000	18	9	61	3	0	86	61	86	61	3	86
2030	27	14	71	4	0	108	68	105	65	5	100
2050	29	18	72	5	0	114	68	110	62	7	101
2100	28	21	74	4	0	118	62	106	53	9	93
Western Europe											
2000	32	108	39	0	0	178	39	178	39	0	178
2030	35	103	45	0	0	183	38	176	42	1	179
2050	35	97	52	0	0	184	38	169	46	1	176
2100	31	92	65	0	0	188	37	160	49	2	170

[a] Total withdrawal calculation, based on the numerator in Eq. 1

[b] The estimated values of the domestic and industrial water withdrawals, and the desalinated water are shared among all of the simulation cases

[c] The values of the reclamation water for the climate fixed case is the same as those for the reference case

[d] MIROC data are utilized for climate change patterns

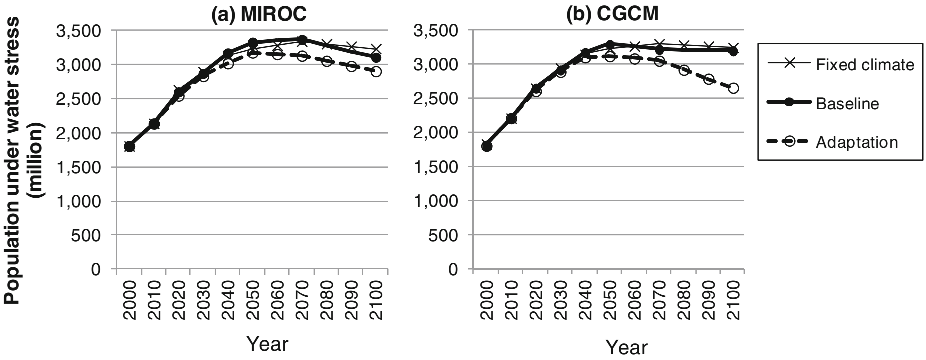


Fig. 8 Projections of the world population affected by water stress in the three simulation cases examined. (For the adaptation cases, all three options mentioned in Section 2.2 are included)

The estimation results for each of the regions examined in the reference case are shown in Fig. 9. This indicates that more than 85 % of the world's water-stressed population was living in North Africa and the Middle East, China, Southeast Asia, India and Other South Asia in 2000. It is estimated that the water-stressed population in these regions will increase significantly during the first half of the 21st century and that, in North Africa and the Middle East and Other South Asia, these increases will continue up to 2100. In the last part of this section, we will now focus on those regions where the largest increases in water-stressed population are expected and examine the likely effects of adaptations.

Figure 10 shows the impacts due to climate change and the effects of the adaptation options on the water-stressed population in 2050 for those regions where the water–stressed population is projected to increase significantly. The followings can be drawn:

> ***China***: The water-stressed population in this region is likely to be reduced by global warming owing to an increase in water availability. It is possible that 'changing varieties and planting times' adaptation may lead to a further reduction because of enhanced land productivity, which will then lead to a decrease in irrigated area. When the adaptations of 'improvement of irrigation efficiency' and 'enhancement of

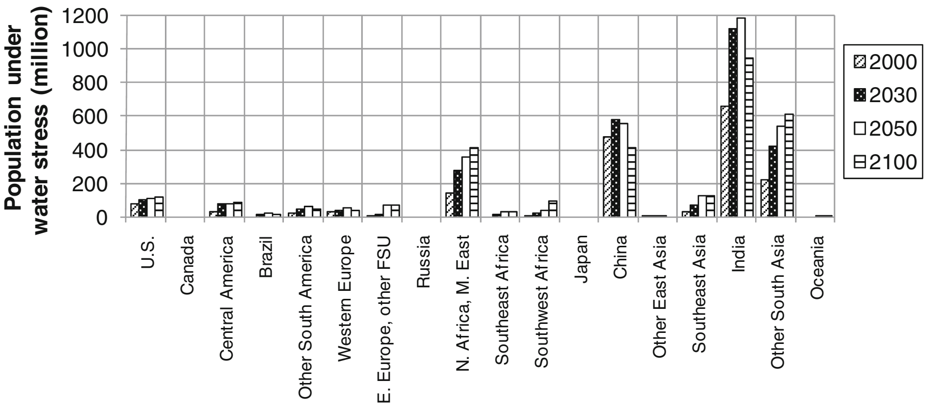


Fig. 9 Population affected by water stress, by region, in the reference case

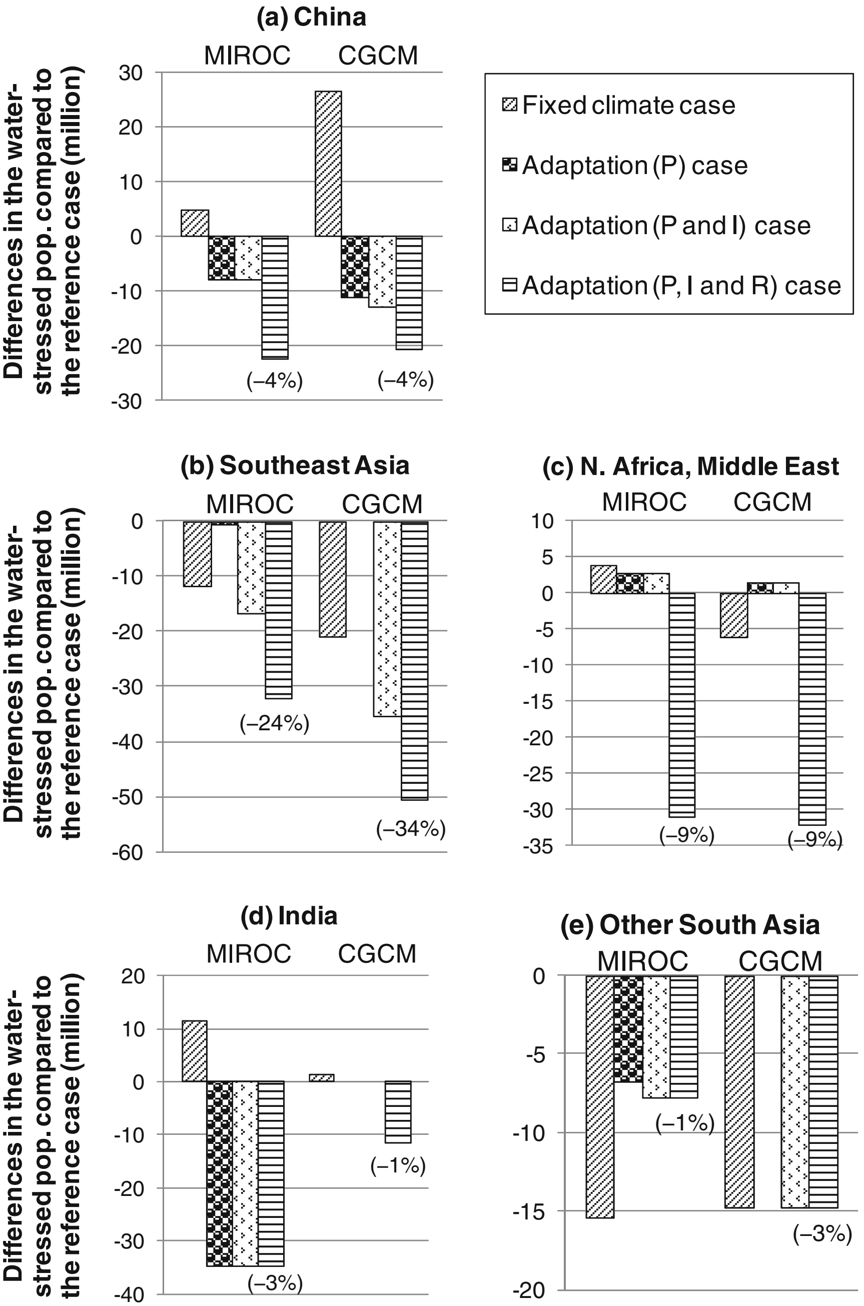


Fig. 10 Impacts due to climate change and effects of different adaptation options on the size of the water-stressed population in 2050 for those regions where the water-stressed population is projected to increase significantly. The vertical axis shows the differences in the water-stressed population compared to the reference case. The letters (P), (I) and (R) represent the adaptation options of ‘changing varieties and planting times’, ‘improvement of irrigation efficiency’ and ‘enhancement of reclamation water’, respectively. The numerical values in parentheses show the percent change of the water-stressed population in the ‘adaptation case (P, I and R)’, relative to the water-stressed population in the reference case

reclamation water' are also implemented, an even greater reduction in the size of the water-stressed population can be expected.

Southeast Asia: It is estimated that the water-stressed population in this region will increase due to global warming, especially in the Philippines. (In the reference case, more than 90 % of the water-stressed population in this region is expected to be found in Indonesia and the Philippines and, due to global warming, the water-stressed population in the Philippines is estimated to increase by 13 million (based on MIROC data) or 21 million (based on CGCM data), compared to the fixed climate case.) The 'changing varieties and planting times' adaptation will enhance the productivity of rice - the dominant crop in this region. However, the amount of irrigation water withdrawal is not likely to be reduced since most of the land available for irrigation is expected to be utilized for rice production in order to meet demand, and rice production requires enormous amounts of water. It is expected that 'improvement of irrigation efficiency' will be one of the key options available to reduce the size of the water-stressed population in this region, especially in the Philippines and Indonesia, and that 'enhancement of reclamation water' will also have the potential to promote further reductions.

North Africa and the Middle East: Due to the uncertainty of climate change projections, both possibilities that the water-stressed population could either increase or decrease due to global warming have been examined. It is not expected that the size of the water-stressed population will be reduced just by 'changing varieties and planting times' since this adaptation does not sufficiently contribute to a reduction in the irrigated area required to meet crop demand. Nor is 'improvement of irrigation efficiency' expected to reduce the water-stressed population because the irrigation efficiency in this region is already relatively high (see Table 1) and the potential for further improvement is limited. Therefore, in this region, 'enhancement of reclamation water' seems to be the key option most likely to reduce water stress.

India: The effects of 'changing varieties and planting times' and 'improvement of irrigation efficiency' are expected to differ, depending on the climate change projections used. However, the 'enhancement of reclamation water' adaptation will probably contribute to reductions in the size of the water-stressed population.

Other South Asia: The size of the water-stressed population in this region will probably increase due to global warming. The estimated effects of 'changing varieties and planting times' are expected to vary, depending on the climate data used. The 'improvement of irrigation efficiency' and 'enhancement of reclamation water' adaptations are expected to alleviate any increase in the water-stressed population due to global warming, although the scale of this effect depends on the climate change projections used.

Further estimations of climate change patterns, based on a larger number of AOGCMs, are needed in order to improve our understanding of the effects of inter-AOGCM differences.

4 Conclusions

This study evaluates the effects of a generic set of agriculture and water management adaptations on the world's water-stressed population for a specific scenario on socio-economic and climate changes during the 21st century. To maintain consistency with agricultural land use change and to take account of adaptations for agriculture and water management, a grid-based water supply–demand model integrated with an agro-land use model was developed, and the size of the water-stressed population evaluated based on a water withdrawals-to-availability ratio for river basins. Key results are summarized as follows:

1) It is estimated that if no adaptations for climate change are implemented the number of people experiencing water stress, worldwide, will increase from 1.8 billion in 2000 to 3.3 billion in 2050 and then stay relatively constant. Even if worldwide GHG emissions are greatly reduced, so that the climate can be maintained at the current level, little reduction in the size of the world's water-stressed population should be expected. It is suggested that the population and economic growths rather than climate change are dominant factors for the increase in the world's water-stressed population.
2) The water-stressed population is likely concentrated in some specific regions. More than 85 % of the world's water-stressed population lived in North Africa and the Middle East, China, Southeast Asia, India and Other South Asia in 2000, and most of the increases during the 21st century are expected to occur in these regions.
3) The key adaptation options to reduce the size of the water-stressed population will differ from region to region, depending on agricultural land use. For instance, in Southeast Asia where rice will be dominant in irrigated areas, the 'improvement of irrigation efficiency' will be one of the key options, and its implementation together with the 'changing varieties and planting times' is expected to decrease the size of the water-stressed population by 17–35 million in 2050 compared to the scenario in which no adaptation options are implemented; Whereas, in North Africa and the Middle East, where irrigation efficiency is already high and there is little potential to improve it further, a reduction in the withdrawal of water use for domestic and industrial purposes by means of the 'enhancement of reclamation water' is expected to be more important. The implementation of the 'enhancement of reclamation water' together with two other options is likely to decrease the size of the water-stressed population in this region by 31–32 million in 2050 compared to the scenario in which no adaptation options are implemented.
4) The worldwide implementation of the all adaptation options adopted in this study can be expected to contribute to a reduction of world water-stress population by about 5 % in 2050 and 7–17 % in 2100, compared to the scenario in which no adaptation options are implemented.

This study evaluates the effectiveness of three adaptation options, which are likely to have the potential to be implemented in most regions of the world, on the size of water-stressed population estimated based on a water withdrawals-to-availability ratio. Possible impacts of heavy rain and drought on annual water availability remain to be addressed in the future research. For individual region, there may be available adaptation options other than the three options adopted in this study, and the actual implementation of adaptations may involve a more complex process than those taken up in this study. The quantitative evaluation on a worldwide basis in this study, maintaining consistency with the scenarios on socio-economic and climate changes provides, nevertheless, a useful and valuable source of information for addressing the adaptive planning at each of the regions and international cooperation.

Acknowledgments This study has been conducted as part of the 'ALPS' (alternative pathways towards sustainable development and climate stabilization) project, supported by the Ministry of Economy, Trade and Industry, Japan. The authors would like to express their sincere gratitude to Professor Yoichi Kaya, President of RITE, Professor Kenji Yamaji, Director General of RITE, and members of the advisory committee of the

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Appendix 1. Outline of the agro-land use model

The agro-land use model developed by Kii et al. (2011) is a grid-based model with 15× 15 min resolution, in which the amounts of cropland required to meet the crop demands are estimated for 32 separate regions, for every decade from 2000 to 2050, and at time points for 2070 and 2100. Crop types include wheat, rice, maize, sugar cane, soybeans, oil palm fruit, rapeseed and others, based on their importance in terms of principal food, favorite food, vegetable oil and feed considerations. The amounts of available land for crop production are allocated in order to meet the regional crop demands. If there is a shortage of crop production due to a lack of available land, production is reallocated to regions where land is still available and any shortage is filled by means of crop trade. The shares of domestic productions relative to the regional demand for each of crops, and the export shares in a global market are maintained to those in 2000 (FAO 2010) except for the case, in which the available land in some regions is not sufficient to meet the crop demand and then the reallocation of production is examined.

Although the model is simplified so that only one selected crop is produced per grid in each analysis year, the regional mean yield for each crop in 2000 is adjusted to reduce the discrepancy with the FAO (2010) statistics less than a few % for most of the 32 regions, and then this simplification is not likely to cause significant estimation errors. It is well justified to utilize in order to quantitatively estimate impacts on the yield and required area due to changes in crop demand, productivity progress, changes on regulation for land use, etc. Furthermore, impacts due to climate change and adaptations for planting can be taken into account through changes in the potential production, which can be calculated using the information on crop characteristics and soil types provided in the GAEZ model for both rain-fed and irrigated conditions. The grids available for irrigation are based on an irrigation map for the year 2000 (Siebert et al. 2007). The regional areas for irrigation maintain the consistency with those of the original map, although the share of irrigation area for each of grids is simplified to be either 0 or 100%. No expansion of the irrigation available grids is allowed in the future according to the assumptions by Alcamo et al. (2007). Our assumption is thought as one of very plausible scenarios, in cases where crop productivities in rain-fed cultivation areas will be robustly improved and the regulations regarding the quality of wastewater will be tightened. The possibility of double cropping is considered for some developing regions, of which the double-cropping area for rice productions are reported (FAO 2009). The double-cropping grids are allocated on the grids with high production potential for rice so that the regional areas may be equal to the statistics. In the world total, approximately 300,000 km^2 in 2000 is considered; and for simplicity, it is assumed that the allocations of double cropping grids will be maintained in the future.

In this study, a partially revised model based on the original agro-land use model is used. Thus, the grid data for arable land in 2000 is updated in accordance with Fischer et al. (2008) and available grids for arable land after 2010 are assumed to can be slightly expanded by including land adjacent to the arable land grids in the previous analysis year (an increase of up to 3 % for each of the 32 regions). Cereals, which are especially important as a principal food crop, are treated preferentially by allocating them to the grids with higher productivity. Furthermore, the assumptions regarding the 'yield factor' are revised.

The 'yield factor' defined as K in Eq. A1 has been introduced by Kii et al. (2011) in order to reduce discrepancies between the regional mean of crop yield, estimated from potential production by the model, and the FAO's statistics (FAO 2009), and to express future improvements in yield cased by factors except for changes on climate, planting area and times, etc..

$$Y = \left(\frac{\sum_i P_i \bullet A_i}{\sum_i A_i} \right) \bullet K \tag{A1}$$

where Y is a regional mean yield for each crop, and i, P and A mean a cultivation grid, potential production (estimated using the GAEZ base module taking climate, soil, slope, varieties of crops and planting times into consideration), and its land area, respectively.

In this study, the scenario of the yield factor (K) is developed taking into account the technological progress associated with economic growths (e.g., mechanization, use of chemical fertilizer) and changes caused by other factors such as land use constraints, agricultural policies, adjustments to price etc. (RITE 2010). The future scenarios on the technological progress and other factors are assumed based on their historical trend during the period of 1961–2006 (FAO 2010). The developed scenario of the yield factor is shown in Table 5. For all crops, a greater growth is expected in developing regions than in developed regions.

Table 5 Scenario describing the yield factors. (Each value is normalized by comparison with 2000)

Crop	Region*	2050			2100		
		Mean	Min.	Max.	Mean	Min.	Max.
Wheat	Developed	1.1	1.0	1.2	1.2	1.1	1.3
Wheat	Developing	1.5	1.1	2.0	1.7	1.3	2.6
Rice	Developed	1.1	1.0	1.2	1.3	1.1	1.4
Rice	Developing	1.6	1.2	6.4	2.1	1.3	7.3
Maize	Developed	1.3	1.0	1.5	1.5	0.9	1.8
Maize	Developing	2.3	1.4	4.0	3.9	2.3	6.5
Sugar cane	Developed	1.0	0.9	1.0	1.0	0.9	1.1
Sugar cane	Developing	1.5	1.0	3.0	1.8	1.0	3.4
Soybeans	Developed	1.1	1.0	1.2	1.2	1.0	1.3
Soybeans	Developing	1.7	1.2	2.3	2.2	1.5	3.5
Oil palm fruit	Developed	0.9	0.9	0.9	0.8	0.8	0.8
Oil palm fruit	Developing	1.4	1.1	1.7	1.8	1.3	2.1
Rapeseed	Developed	1.2	0.9	1.4	1.3	0.9	1.5
Rapeseed	Developing	1.5	1.0	2.0	1.9	1.1	2.6
Others	Developed	1.2	1.1	1.3	1.3	1.2	1.5
Others	Developing	1.4	1.1	2.1	1.8	1.1	2.7

* Developed regions include the United States, Canada, Western Europe, Japan and Oceania (out of the 32 regions used for the agro-land use model)

Appendix 2. Domestic water withdrawal per 'access-person' in urban and rural areas

The relationships between per 'access-persons' withdrawal and per capita GDP are formulated by Eq. A2, which was estimated by regression analysis using several country-statistics for the period of 1990–2004. That is the statistics for domestic water withdrawal (FAO 2009), per capita GDP (World Bank 2008) and 'access-persons' in urban and rural areas (World Bank 2008)). In order to separate the domestic water withdrawal reported by FAO into those for urban and rural areas, the per capita domestic water demand for each of areas in several regions of the world (refer to Table 4.4 of Rosegrant et al. 2002) were adopted:

$$\left.\begin{aligned} DW_{t,c} &= k_c \times DW0_{t,c} \\ \log DW0_{t,c} &= \left(a \times per\ capita\ GDP_{t,c}\right) / \left(b + per\ capita\ GDP_{t,c}\right) \end{aligned}\right\} \tag{A2}$$

where the subscript *t* and *c* indicate the time point and country, respectively, DW is per 'access-persons' withdrawal, *a* and *b* are regression coefficients (a=1.98 and b=83 for urban areas, and a=1.88 and b=127 for rural areas), and *k* is a factor to reduce discrepancies between the per 'access-persons' withdrawal estimated by the regression function and the amount by statistics for the year of 2000. Based on the relationships studied, per 'access-persons' withdrawal is expected to increase in both of urban and rural areas associated with the economic growth.

Appendix 3. Scenarios for the industrial water requirement and water-use efficiency

The 'weighted production' and the energy-use efficiency for the production of crude steel by blast furnaces are used as proxies for the industrial water requirements and the water-use efficiency, respectively, as mentioned in Section 2.1.3. Table 6 shows values used in this study for these proxies. The data up to the year 2050, have been obtained from the DNE21+ model and, from 2050 on, estimates are extrapolated based on the assumption that the annual change rate will gradually decrease.

Appendix 4. The ratio of urban population relative to total population

According to the UN survey (2009), the specific conditions and terms used to describe the 'urban' population can differ from country to country. For instance, although the ratio of non-agricultural workers is considered in some countries such as China, India and Russia, such occupations are not specified in most countries and other descriptive terms are used, such as 'the population density is above a certain level' and 'several public infrastructure constructions have been carried out'. We assumed that the urban population ratio (*UP*) was represented by a function of the population density (*D*) and per capita GDP (used as a proxy for the construction of infrastructure), as denoted by Eq. A3, and the parameters α_1 and α_2 are estimated for each country using regression analyses based on statistical data from 1960–2005 (i.e., data for the urban population ratio (UN 2009), area per country, and per capita GDP (World Bank 2008)).

$$UP_{rt} = \alpha_{1r} \bullet \left(\log(per\ capita\ GDP_{rt} \bullet D_{rt})\right)^{\alpha_{2r}} \tag{A3}$$

where *r* and *t* are the country and the time point, respectively. This equation shows that the urban population ratio increases with growth in per area GDP. Determination coefficients for the past of about 50 years are over 0.8 for 97 out of the 135 countries which comprised 91 % of the world's population in 2000.

Table 6 Scenario describing the 'weighted production' and the energy-use efficiency for the production of crude steel by blast furnaces. The values in 2000 and the annual change rates are listed for the top twenty 'weighted production' regions in 2050 among the 54 regions defined for the DNE21+ model, which are expected to occupy the approximately 90 % of the world 'weighted production' during the 21st century

	Weighted production			Energy-use efficiency		
	in 2000 (Mton)	Rate of change (% p.a.)		in 2000 (TOE/ton)	Rate of change (% p.a.)	
		2000–2050	2050–2100		2000–2050	2050–2100
China	463	3.33	0.10	0.62	-0.36	-0.08
United States	889	0.15	0.02	0.70	-0.56	-0.11
India	70	4.78	0.57	0.72	-0.63	-0.09
North Europe	222	1.65	0.38	0.76	-0.72	-0.11
Russia	116	2.50	0.48	0.76	-0.70	-0.15
Indonesia	67	3.45	0.74	0.67	-0.52	-0.07
Brazil	88	2.68	0.49	0.77	-0.74	-0.12
Japan	394	-0.36	-0.14	0.59	-0.25	-0.07
Canada	206	0.76	0.36	0.75	-0.69	-0.13
Germany	214	0.53	-0.03	0.64	-0.43	-0.07
Korea	131	0.89	0.06	0.63	-0.34	-0.10
Mexico	51	2.14	0.38	0.77	-0.79	-0.07
Turkey	28	3.19	0.34	0.79	-0.77	-0.15
Thailand	24	3.21	0.49	0.67	-0.49	-0.11
France	113	0.03	-0.01	0.74	-0.65	-0.12
Spain, Portugal	72	0.87	0.00	0.77	-0.73	-0.14
Italy	109	-0.06	-0.05	0.74	-0.63	-0.15
Other Annex I of East Europe	33	2.27	0.47	0.76	-0.73	-0.10
Other EU	53	1.20	0.20	0.72	-0.64	-0.10
South Africa	36	1.52	0.44	0.81	-0.72	-0.20
World	3,853[a]	1.69	0.27	0.73[b]	-0.63	-0.10

[a] The world total

[b] The mean of the efficiencies for the 54 regions

Appendix 5. Grid-based distributions of population and urban areas

Scenarios for population distribution and urban areas (for every 10 years from 2000 to 2100) were developed based on population maps for the year 2000 (PBL 2009) with 5×5 min of resolution. First, the original PBL's total population map was adjusted to agree with the ALPS country-level population data, by applying the same factor to the grids within one country. Then, population distributions after 2010 were estimated so that the population in each grid will change in proportion to its population density as denoted by the following Eq. (A4).

$$p_{i,t+1} = p_{i,t} + (p_{i,t}/P_t) \times (P_{t+1} - P_t) \tag{A4}$$

where the P is a number of population for a specific country, and subscript t is the time point. The $p_{i,t}$ indicates the number of population of grid i, which is included in the country. This allocation rule is based on a study by Grübler et al. (2007), which reflects a well-observed pattern of the concentration to urban areas and the spread to areas located in close to proximity.

Grids for urban areas in 2000 were specified based on the PBL's urban population map so that the number of population included in the urban grids agrees with the ALPS country-level urban population data, by slightly shifting the PBL's original boundaries between urban-rural areas. For the estimations of urban grids after 2010, it was assumed that a grid classed as urban will be the most likely to become urban in the next future time point. The urban-rural boundaries were adjusted for each of the time points so that population included in the urban grids agrees with the ALPS country-level urban population data.

Appendix 6. Scenarios for food demand

The scenario for per capita dietary energy demand was developed based on the logistic functions of per capita GDP, which were estimated by regression analysis for each of the 32 regions assuming that the per capita food demand will increase associated with the economic growth, and will be saturated at a specific amount. For the analysis, the data during the period of 1961–2005 (FAO 2010; World Bank 2008) were utilized. Figure 11(a) shows the developed scenario for major regions. It should be noted that this demand includes household.

It was assumed that the demand was divided into the demand for four classes of food (i.e., cereals and vegetables, animal products, sugar, and oil). The increases in the shares for animal products, sugar and oil associated with economic growth were projected based on the logistic functions of per capita GDP, which were estimated by regression analysis for the each region. Figure 11(b) shows the scenario for the shares by food classes in the world. It is assumed that preference of animal products, oil and sugar will be enhanced throughout this century.

Furthermore, demand of the animal products was converted to the feed crop demand, and the oil and sugar demand were converted to the ingredient crop demand. Finally, the demands of the four food classes were aggregated to the demand by each of the eight specific crops adopted in the agro-land use model (i. e. wheat, rice, maize, sugar cane, soybeans, oil palm fruit, rapeseed and others) (RITE 2010, 2011a).

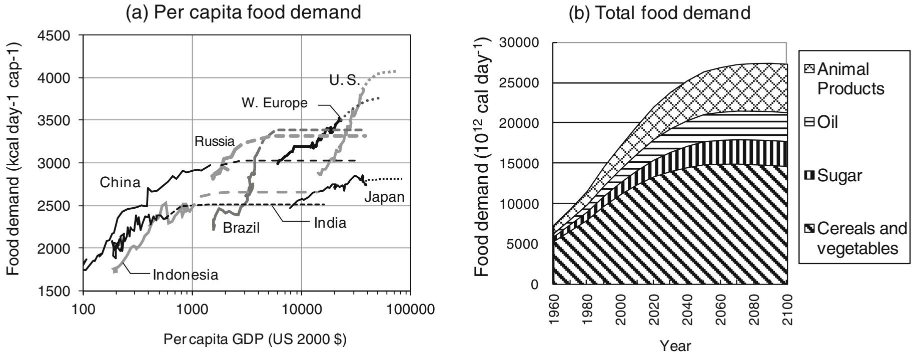

Figure 11 (**a**) Per capita food demand for major regions and (**b**) Shares of dietary energy demand by the four food classes in the world. In Figure (**a**), solid lines are based on the FAO's statistic, and dashed line show scenarios developed in this study. In Figure (**b**), values after 2005 are based on the developed scenarios

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