Ecological Indicators 43 (2014) 29–35

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Decoupling agricultural water consumption and environmental impact from crop production based on the water footprint method: A case study for the Heilongjiang land reclamation area, China

Zhang Yu, Yang Qingshan*

School of Geographical Science, Northeast Normal University, Changchun 130024, China

ARTICLE INFO

Article history:
Received 19 June 2013
Received in revised form 3 February 2014
Accepted 9 February 2014

Keywords:
Decoupling
Water footprint
Crop production
Agricultural water consumption
Environmental impact

ABSTRACT

Crop production consumes and pollutes large volumes of water. Previous literature predominantly discusses a single indicator of agricultural water consumption or environmental impact from crop production. This study integrates a water footprint method into a decoupling analysis. The water footprint method uses multidimensional indicators to illustrate agricultural water consumed or polluted in crop production according to its elements and sources. Using the largest commodity grain in China during the years 2000–2009 as a case study, this research focuses on the analysis of decoupling agricultural water consumption and environmental impact from crop production based on two indexes, D_{Y-WC} and D_{Y-WEI}. The results show the following: (1) a strong decoupling trend occurred more in the analysis of decoupling agricultural water consumption from crop production; (2) weak decoupling occurred more often in the analysis of decoupling agricultural water environmental impact from crop production.

1. Introduction

The term "decoupling" (or de-linking) originates from the field of physics with the idea of "uncoupling", meaning that the mutual relationship between two or more physical quantities no longer exists. Decoupling refers to breaking the link between "environmental bads" and "economic goods", and decoupling environmental pressure from economic growth is one of the primary objectives of the OECD Environmental Strategy for the First Decade of the 21st Century (OECD, 2002). The decoupling state has been adopted as a policy goal in the European Union, and decoupling human well-being from resource consumption is at the heart of the Green Economy Initiative of UNEP (UNEP, 2011).

Decoupling analysis is becoming increasingly popular for measuring the relationship between resource use (environmental impact) and economic activity (OECD, 2003; Tapio, 2005; Jarmo et al., 2007; Enevoldsen et al., 2007; Lu et al., 2007; Massimiliano and Roberto, 2008; Mazzanti, 2008). A stylized representation of resource decoupling and impact decoupling is shown in Fig. 1 (UNEP, 2011). In studies of agricultural production, the available literature focuses on decoupling cultivated land occupancy from GDP growth, but the topic of crop production is addressed less frequently. For example, He et al. (2005) carried out an agricultural eco-environment assessment according to a decoupling index system on soil erosion, Yu (2008) generated a set of criteria for decoupling crop production from irrigation water, and Xu et al. (2010) analyzed the relationship between fertilizer application and crop production using panel data (1999–2007) of 31 provincial areas in China.

Water is an element of production and the base of the ecosystem; the properties of water resources and the water environment are inseparable. In the field of agricultural production, the dual properties of agricultural water include both water consumption and water environmental impact due to the application of fertilizers and pesticides. Therefore, the analysis of decoupling agricultural water from crop production inevitably involves two factors: agricultural water consumption and water environmental impact. The water footprint (WF) method integrates the dual properties of water and tracks the footprints of agricultural water in terms of the blue water footprint, the green water footprint and the gray water footprint of crop production. However, a decoupling analysis of agricultural water from crop production based on the water footprint has not been reported to date.

2. Study area

The Heilongjiang land reclamation area (HLRA) is located in the world-famous Blacklands of China; it has an area of approximately 57,600 km^2, including 113 farms located on 9 branches (Fig. 2). The

* Corresponding author. Tel.: +86 43185099550.
E-mail addresses: zhangy221@nenu.edu.cn (Z. Yu), yangqs027@163.com (Y. Qingshan).

http://dx.doi.org/10.1016/j.ecolind.2014.02.010
1470-160X/

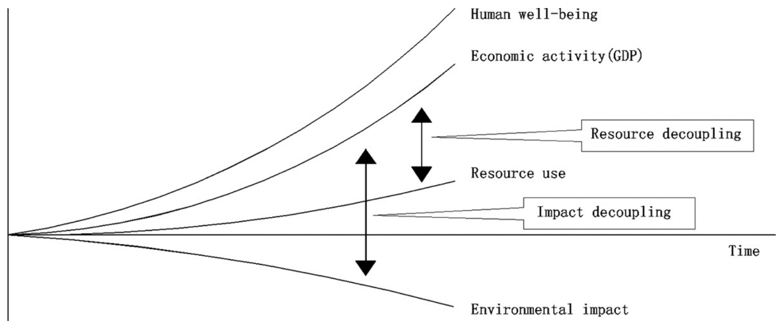

Fig. 1. Stylized representation of two aspects of decoupling (source: UNEP, 2011).

climate ranges from humid to semi-humid, with an average precipitation of approximately 540 mm/year, and the growing season precipitation (May–September) accounts for 80–90% of the yearly rainfall. The study area is divided into two parts: the humid eastern four branches and the semi-humid western five branches. Crops appropriate for the HLRA include rice, corn, soybean and wheat; the yields of these crops accounted for 94% of the sum total in 2011. In the HLRA, the cultivated land area per capita is 15 times greater than the national average, and the crop yield per unit area exceeds that of the USA; thus, this area represents highest production capacity in China.

Economic growth in the HLRA has been very costly, especially in terms of water resources and the water environment. Since 2000, the rice planting areas in the eastern Sanjiang plain have increased in size quickly because of economic factors, while local irrigation systems lag behind and well-irrigated areas for rice makeup 80–90% of the entire rice planting area. As a result, land subsidence occurs widely, and the average groundwater recession in the eastern Sanjiang plain is 2.5 m (Liu et al., 2006). Moreover, the non-point source pollution caused by chemical fertilizers in crop production constitutes over 80% of the total pollution in the HLRA, which has become the largest hidden threat to food and ecological security. Using this largest green grain production base in China as an example, do the high yields come with high energy costs, high material consumption, and high pollutant emission in the HLRA? By focusing on these questions, decoupling analysis of agricultural water from crop production contributes to constructing an “ecological, intelligent and low carbon” agricultural production system.

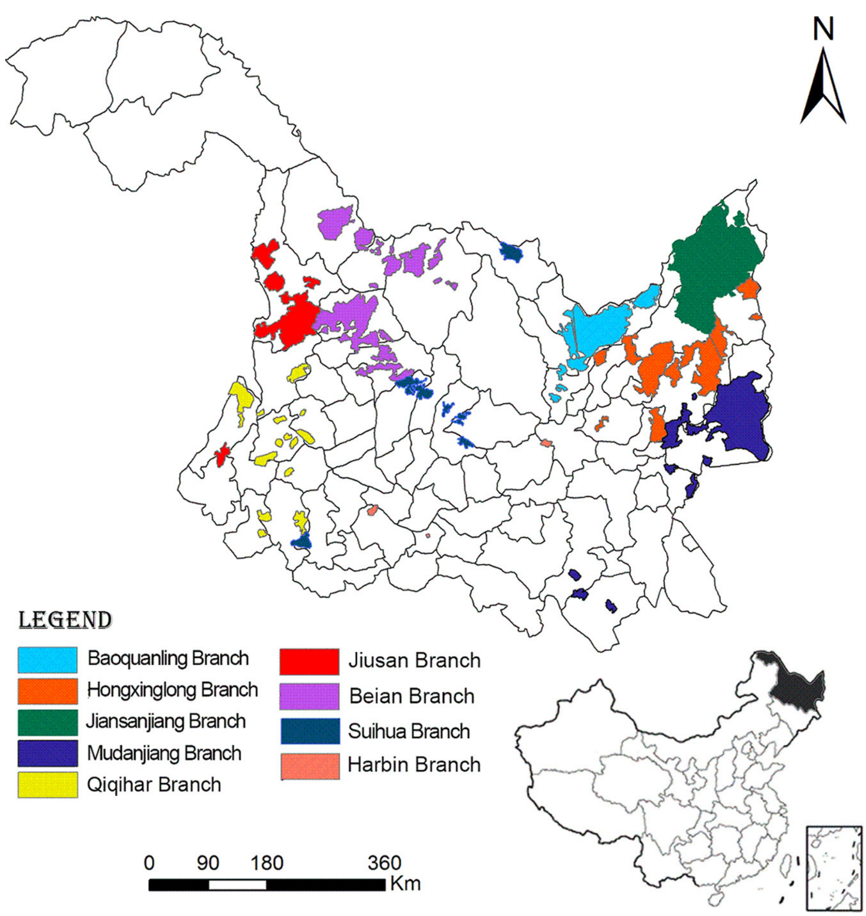

Fig. 2. Location of the Heilongjiang land reclamation area (HLRA) in China.

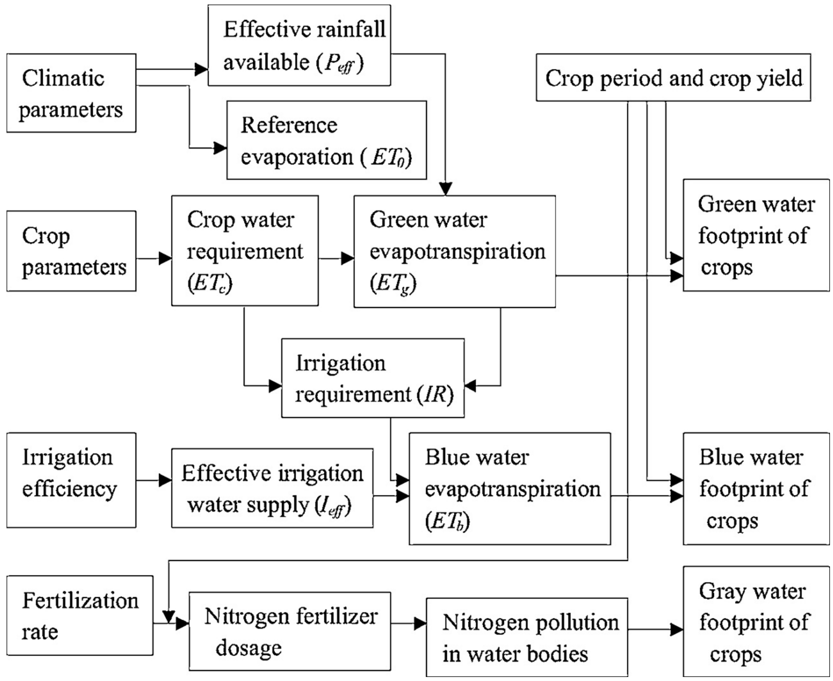

Fig. 3. Diagram of calculating the water footprint of a primary crop in the HLRA. It is adapted from Chapagain and Orr (2008), Aldaya and Llamas (2008) and replenished calculating of the gray water footprint. The formulas used to calculate the blue, green and gray water footprints and the meaning of the related variables can be found in the literature Hoekstra and Hung (2005), Chapagain and Hoekstra (2010).

3. Material and methods

3.1. Method of water footprint

Similar to the concept of ecological footprint, the concept of water footprint was introduced by Hoekstra and Hung (2002) and was subsequently elaborated on by Hoekstra and Chapagain (2008). The water footprint of a product (alternatively known as "virtual water content", Allan, 2003), is the sum of the water footprints of the process steps taken to produce the product measured over the entire supply chain within a country or a region. Its multidimensional indicators show water consumption volumes by sources and polluted volumes by type of pollution (Mekonnen and Hoekstra, 2011; Hoekstra et al., 2011). Three elements of the water footprint (the green, blue and gray water footprints) are specified geographically and temporally. The blue water footprint refers to the volume of surface and groundwater consumed (it does not include blue water use insofar as this water is returned to where it came from) during crop production, and the green water footprint refers to the rainwater consumed (rainwater stored in the soil as soil moisture) during crop growth (Hoekstra et al., 2011). Thus, the total volume of agricultural water consumed for crop production is the sum of the blue and green water footprints (Falkenmark, 1995; Hoekstra, 2003; Graham, 2006; Monireh et al., 2009; Zeng et al., 2012). Additionally, fertilizers and pesticides applied during crop growth often cause water pollution, and the gray water footprint refers to the volume of freshwater that is required to assimilate the load of pollutants, based on existing ambient water quality standards (Hoekstra et al., 2011). From the perspective of crop production, Mekonnen and Hoekstra (2011) estimated the green, blue and gray water footprints of 126 crops globally during 1996–2005 with high spatial resolution.

The importance of using the water footprint method in a decoupling analysis is that it offers a wider perspective on the study of agricultural water, taking into account the total volumes of water consumed and polluted in the annual production of a certain crop. The virtual water and water footprints of crops in the HLRA (2000–2009) are calculated as Fig. 3.

3.2. Data sources

The data sources used for the water footprint accounting in this study include climate data and crop production data. Climatic data include average monthly rainfall, evapotranspiration, temperature, sunshine, humidity, wind speed and radiation data as inputs for the CROPWAT model (FAO, 2010; Allen et al., 1998). Climatic data were obtained from China Meteorological Data Sharing Services System (http://cdc.cma.gov.cn/home.do) and 8 weather stations near the HLRA (stations at Fujin, Jiamusi, Jixi, Mudanjiang, Hailun, Harbin, Nenjiang and Qiqihar).

The CROPWAT model for water footprint accounting in crop production also requires crop and soil parameters to model evapotranspiration and crop irrigation requirements. Crop parameters included rooting depths, crop coefficients, planting and harvest dates, and lengths of developmental stages for each crop, as described in studies by Allen et al. (1998) and Chapagain and Hoekstra (2004). The predominant soil types are black soil, meadow soil and Baijiang soil in the study area, and soil parameters included maximum infiltration rate, values of available soil water content, maximum rooting depth, and initial soil moisture depletion. Available soil water content and the maximum infiltration rates were obtained from the soil nutrient database of Heilongjiang Academy of Land Reclamation Sciences. Crop yield data came from the Statistic Yearbook of the Heilongjiang land reclamation area (2001–2010). Agricultural water environmental impact is based on the standard of the United States Environmental Protection Agency (Environmental Protection Agency (EPA), 2005). The fertilizers applied included urea, diammonium phosphate, potassium chloride and potassium sulfate. Nitrogen (the most substantial component of the fertilizers) is used as the case pollutant. The nitrogen leaching rates of rice, wheat, corn, and soybeans during crop growth came from field research conducted by Zhang, et al. (2000),

Table 1
Criteria for degrees of decoupling/coupling agricultural water consumption and environmental impact from crop production.

Degrees of decoupling/coupling	Relationship between crop yield and water consumption	Relationship between crop yield and water environmental impact
Strong decoupling	$\Delta WC \leq 0$, $\Delta Y > 0$	$\Delta WEI \leq 0$, $\Delta Y > 0$
Strong coupling	$\Delta WC \geq 0$, $\Delta Y < 0$, $D_{Y-WC} \leq 0$	$\Delta WEI \geq 0$, $\Delta Y < 0$, $D_{Y-WEI} \leq 0$
Weak decoupling	$\Delta WC > 0$, $\Delta Y > 0$, $0 < D_{Y-WC} < 1$	$\Delta WEI > 0$, $\Delta Y > 0$, $0 < D_{Y-WEI} < 1$
Expansive coupling	$\Delta WC > 0$, $\Delta Y > 0$, $D_{Y-WC} \geq 1$	$\Delta WEI > 0$, $\Delta Y > 0$, $D_{Y-WEI} \geq 1$
Weak coupling	$\Delta WC < 0$, $\Delta Y < 0$, $0 < D_{Y-WC} < 1$	$\Delta WEI < 0$, $\Delta Y < 0$, $0 < D_{Y-WEI} < 1$
Recessive decoupling	$\Delta WC < 0$, $\Delta Y < 0$, $D_{Y-WC} \geq 1$	$\Delta WEI < 0$, $\Delta Y < 0$, $D_{Y-WEI} \geq 1$

Han, et al. (2003) and Zhang et al. (2007); these rates were 14%, 13%, 12%, and 5% in the eastern areas, and 12%, 11%, 10% and 4% in the western areas, respectively.

It should be noted that international scientific research on gray water footprint accounting only considers pollutants from fertilizer application; pesticides and herbicides have not been considered because of their complexity. The application of chemical pesticides in the HLRA is only 3.69 kg/ha (pure quantity), which is far below the national standard (15.23 kg/ha). In this regard, the gray water footprint reported in this study is relatively conservative; however, it may reflect the status of agricultural production in the HLRA.

3.3. Indicators of decoupling analysis

Different methods have been applied to the decoupling analysis of resource use or environmental impact from economic development, including decoupling indexes, comprehensive analysis of variation, elasticity indexes, the IPAT model, metrological analysis, descriptive statistical analysis, and differential regression coefficients.

Our research on the decoupling issue addresses changes in agricultural water consumption (WC), changes in agricultural water environmental impact (WEI), and changes in crop yield (Y). Referring to the available literature on the elasticity indexes approach (Tapio, 2005; Zhong et al., 2010; Wu et al., 2011), this research constructs two decoupling elastic indexes: D_{Y-WC} for decoupling water consumption from crop yield, and D_{Y-WEI} for decoupling water environmental impact from crop yield. These indexes are computed using the following formulas:

$$D_{Y-WC} = \frac{\%\Delta WC}{\%\Delta Y} = \frac{(WC_i/WC_{i-1} - 1)}{(Y_i/Y_{i-1} - 1)} \quad (1)$$

$$D_{Y-WEI} = \frac{\%\Delta WEI}{\%\Delta Y} = \frac{(WEI_i/WEI_{i-1} - 1)}{(Y_i/Y_{i-1} - 1)} \quad (2)$$

In the above formulas, WC is the sum of the blue water footprint and the green water footprint (i.e., the blue-green water footprint) in crop production; WC_i and WC_{i-1} represent agricultural water consumption in the last phase and the base period, respectively. Similarly, WEI is the volume of the gray footprint in crop production; WEI_i and WEI_{i-1} represent agricultural water environmental impact in the last phase and the base period, respectively. Y_i and Y_{i-1} represent the crop yield in the last phase and the base period, respectively. Using the difference (Δ) between the volume of agricultural water consumption, agricultural water environmental impact or crop yield at two points in time (the time interval is one year in this study), $\%\Delta WC$ is the growth rate of agricultural water consumption between the last phase and the base period, $\%\Delta WEI$ is the change rate of agricultural water environmental impact from the last phase to the base period, and $\%\Delta Y$ is the growth rate of crop yield from the last phase to the base period. Six possible combinations of change in the variables WC, Y and WC/Y can be interpreted as different degrees of the decoupling/coupling process. The six possible combinations of change in the variables WEI, Y and WEI/Y can be interpreted in the same way (Table 1).

Based on the measuring model and criteria for decoupling analysis, this study analyzes the relationship between crop production and agricultural water consumption and water environmental impact in the HLRA (2000–2009).

4. Results

4.1. Relationship between crop yield and the blue-green water footprint

The changes in the crop yield and agricultural water consumption (expressed by the blue-green water footprint in crop growth) in the HLRA (2000–2009) are shown in Fig. 4; the correlation coefficient, R, between crop yield and the blue-green water footprint is 0.797 at the 0.01 significance level. Using crop production as the independent variable, x, and the blue-green water footprint as the dependent variable, y, the equation used to relate the two factors is $y = 53.825 + 0.039x$. The R^2 and adjusted R^2 values of this equation are 0.636 and 0.590, respectively, and the F test value is 13.962, which is close to 11.3 at the 0.01 significance level and passes the F test.

4.2. Relationship between crop yield and the gray water footprint

The changes in crop yield and water environmental impact caused by fertilizer application (expressed as the gray water footprint in crop growth) in the HLRA (2000–2009) are shown in Fig. 5; the correlation coefficient, R, between the crop yield and the gray water footprint is 0.987 at the 0.01 significance level. Using crop production as the independent variable, x, and the gray water footprint as the dependent variable, y, the equation used to relate these two factors is $y = 11.266 + 0.021x$; the R^2 value is 0.975 and the

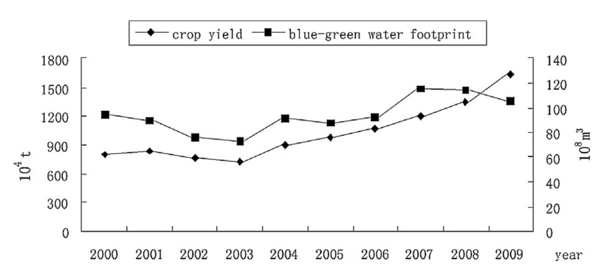

Fig. 4. Crop yield and the blue-green water footprint in the HLRA (2000–2009).

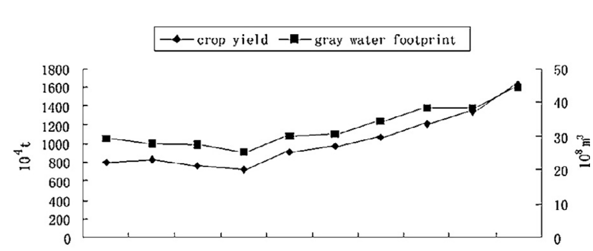

Fig. 5. Crop yield and the gray water footprint in the HLRA (2000–2009).

Table 2
Decoupling/coupling agricultural water consumption from crop production in the HLRA.

Year	Crop yield (10^4 t)	Growth rate of crop yield (%)	Blue-green water footprint (10^8 m^3)	Growth rate of blue-green water footprint (%)	D_{Y-WC}	Degrees of decoupling/coupling
2000	796.133	–	94.28	–	–	–
2001	832.17	4.53	89.4	−5.18	−1.14	Strong decoupling
2002	761.31	−8.52	76.25	−14.71	1.73	Recessive decoupling
2003	717.41	−5.77	72.48	−4.94	0.86	Weak coupling
2004	901.22	25.62	91.3	25.97	1.01	Expansive coupling
2005	973.10	7.98	87.36	−4.32	−0.54	Strong decoupling
2006	1065.11	9.46	92.77	6.19	0.65	Weak decoupling
2007	1210.07	13.61	115.57	24.57	1.81	Expansive coupling
2008	1337.51	10.53	114.38	−1.02	−0.10	Strong decoupling
2009	1631.90	22.01	105.96	−7.36	−0.33	Strong decoupling

Table 3
Decoupling/coupling agricultural water environmental impact from crop production in the HLRA.

Year	Crop yield (10^4 t)	Growth rate of crop yield (%)	Gray water footprint (10^8 m^3)	Growth rate of gray water footprint (%)	D_{Y-WEI}	Degrees of decoupling/coupling
2000	796.13	–	29.05	–	–	–
2001	832.17	4.53	27.75	−4.48	−0.99	Strong decoupling
2002	761.31	−8.52	27.3	−1.62	0.19	Weak coupling
2003	717.41	−5.77	25.2	−7.69	1.33	Recessive decoupling
2004	901.22	25.62	29.9	18.65	0.73	Weak decoupling
2005	973.10	7.98	30.72	2.74	0.34	Weak decoupling
2006	1065.11	9.46	34.47	12.21	1.29	Expansive coupling
2007	1210.07	13.61	38.2	10.82	0.79	Weak decoupling
2008	1337.51	10.53	38.42	0.58	0.06	Weak decoupling
2009	1631.90	22.01	44.68	16.29	0.74	Weak decoupling

adjusted R^2 value is 0.971. The goodness of fit of the equation is high, and the high R^2 value indicates a close relationship between the gray water footprint and the crop yield, especially in the years 2008 ; and 2009.

4.3. Decoupling agricultural water consumption from crop production

Based on the criteria for decoupling degrees (Table 1) and the blue-green water footprint, the results of the decoupling/coupling analysis are shown in Table 2.

In the period 2000–2009, the trend of strong decoupling occurred for 4 years, and recessive decoupling and weak decoupling occurred for 1 year each. The volumes of agricultural water consumption did not increase in proportion with crop yield in the HLRA in the years 2001, 2005, 2008 and 2009. However, the expansive coupling state is a warning of the problem of groundwater overexploitation, especially for the eastern branches with large planting areas.

4.4. Decoupling agricultural water environmental impact from crop production

Based on the perspective of the gray footprint, the results of decoupling/coupling agricultural water environmental impact from crop production in the HLRA (2000–2009) are shown in Table 3.

The results show that the trend of weak decoupling occurred for 5 years, strong decoupling and recessive decoupling occurred for 1 year each, and weak coupling and expansive coupling occurred for 1 year each. These findings indicate that even if we estimate the water pollution associated with the use of nitrogen fertilizer only in crop production, water environmental stress caused by fertilizer application still exists in the HLRA; there is much room for improvement in building a green agricultural production system.

4.5. Example: decoupling agricultural water consumption and environmental impact from rice production

Rice is a globally important cereal plant and a primary source of food, and rice accounts for a larger share of consumptive water use in cropland in the HLRA. In the period 2000–2009, the blue-green water footprint of rice constituted 50% of all crops' blue-green water footprint, and the gray footprint of rice constituted 56% of all crops' gray footprint in this area (as shown in Fig. 6 and Table 4).

Further results of the analysis decoupling agricultural water consumption and environmental impact from rice production (average of the years 2000–2009) are shown in Table 5.

In the case study of decoupling agricultural water consumption and environmental impact from rice production in the HLRA in the period 2000–2009, the trend of weak decoupling was typical in those branches with large rice planting areas (including

Table 4
Comparison of international gray water footprint of rice (average for the years 2000–2004). Data in the table are from Hoekstra and Chapagain (2008).

Country (region)	Gray water footprint of rice (unit: m^3/t)
Heilongjiang land reclamation area	312
China	117
America	101
India	116
Indonesia	118
Bangladesh	103
Vietnam	127
Thailand	116
Burma	50
Japan	61
Philippines	78
Brazil	61
North Korea	84
Pakistan	88
Average	109

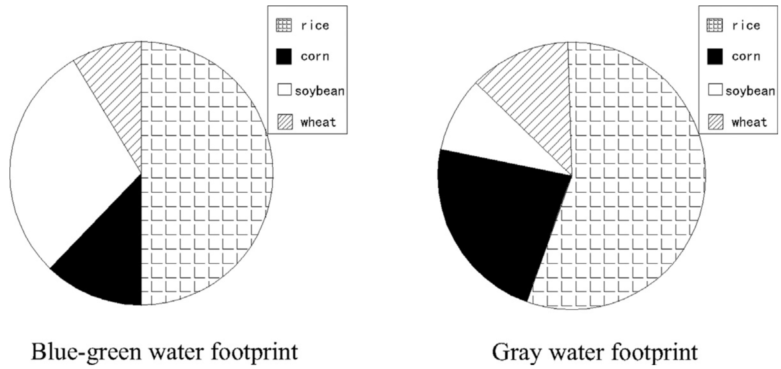

Fig. 6. Water footprints of the main crops in the HLRA (2000–2009).

Table 5
Decoupling analysis of agricultural water consumption and water environmental impact from rice production in the HLRA. (Average of the years 2000–2009).

Branch	Growth rate of rice yield (%)	Growth rate of blue-green water footprint of rice (%)	Growth rate of gray water footprint of rice (%)	D_{Y-WC}	D_{Y-WEI}	Decoupling degrees of WC from *Y*	Decoupling degrees of WEI from *Y*
BQL branch	0.06	0.03	0.02	0.50	0.33	Weak decoupling	Weak decoupling
HXL branch	0.03	0.01	0.02	0.33	0.67	Weak decoupling	Weak decoupling
JSJ branch	0.13	0.09	0.09	0.69	0.69	Weak decoupling	Weak decoupling
MDJ branch	0.04	0.02	0.03	0.50	0.75	Weak decoupling	Weak decoupling
BA branch	0.52	0.29	0.02	0.56	0.04	Weak decoupling	Weak decoupling
JS branch	0.06	0.05	0.03	0.83	0.50	Weak decoupling	Weak decoupling
QQH branch	0.07	0.04	0.06	0.57	0.86	Weak decoupling	Weak decoupling
SH branch	0.01	−0.01	0.03	−1.0	3.00	Strong decoupling	Expansive coupling
HB branch	0.05	−0.06	0.06	−1.20	1.20	Strong decoupling	Expansive coupling

Jiansanjiang branch, Mudanjiang branch, Hongxinglong branch, and Baoquanling branch in Table 5). It is possible for these branches to achieve the strong decoupling state by improving water use and fertilizer application efficiency. In particular, more attention should be paid to preventing groundwater overexploitation for the eastern branches. For branches with small rice planting areas, Suihua Branch and Harbin Branch achieved strong decoupling of water consumption from rice production but had expansive coupling of water environmental impact from rice production; it is urgent to improve fertilizer application efficiency in these branches. At present, testing soil for formulated fertilizers has been instituted in 90% of the HLRA, and tracking and evaluating the gray water footprint of crop production will contribute to protecting the water environment.

5. Discussion and conclusion

Establishing a resource-saving and environmentally friendly agricultural production system is the goal of China's agricultural development. As for agricultural water use, we have not yet found ways to properly address problems of water scarcity and pollution, and the lack of methods for integrating the dual properties of water resources and the environment hampers the evaluation of agricultural water use. Different from the conventional way of measuring freshwater use by gross water withdrawals, the "water footprint" method measures consumptive water use and the volume of water polluted (Hoekstra, 2013). In this study, the water footprint method is employed for the first time in a decoupling analysis of agricultural water use and crop production.

The water footprint provides a framework to analyze water consumption volumes by source and polluted volumes by type of pollution from a wider perspective. Much work needs to be performed to perfect this method, such as further separating the use of green and blue surface and groundwater to create more effective human intervention towards a better eco-environment; calculating the gray water footprint associated with the use of pesticides and herbicides (other than nitrogen fertilizers) in crop production for a more comprehensive water environmental evaluation; and most importantly, building water footprint benchmarks for water-using processes to provide an incentive to producers to reduce the water footprint of their products (Hoekstra, 2013). All these improvements will contribute to a more objective decoupling analysis of agricultural water use and crop production.

Using the water footprint indicators and building two elastic indexes (D_{Y-WC} and D_{Y-WEI}), this research analyzed the relationship between crop production and agricultural water consumption and agricultural water environmental impact in the Heilongjiang land reclamation area. The results show that crop production was not impacted by agricultural water consumption in the period 2000–2009 over the entire study area, but the problem of groundwater overexploitation cannot be ignored in the eastern branches. Moreover, the weak decoupling trend was prominent according to our results (in this study, we have quantified the gray water footprint related to nitrogen use only), and the threat of water pollution still exists. These results will help local decision-makers to adopt active human interventions toward improving agricultural water management and achieving a green agricultural production system.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (grant numbers 41071088 and 41271555). We thank Yu Yongqiang, Su Mingtao, Zhang Chuanping and Liu Hehe for their support in this study. We would also like to thank the anonymous reviewers of the journal for their contributions.

References

Aldaya, M.M., Llamas, M.R., 2008. Water footprint analysis for the Guadiana river basin. Value of Water Research Report Series No. 35. UNESCO-IHE, Delft, Netherlands www.waterfootprint.org/Reports/Report35-WaterFootprint-Guadiana.pdf.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization, Rome.

Allan, J.A., 2003. Virtual water – the water, food, and trade nexus: useful concept or misleading metaphor? Water Int. 28 (1), 106–113.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations. Volume 1: main report. Value of Water Research Report Series No. 16. UNESCO-IHE, Netherlands www.waterfootprint.org/Reports/Report16.pdf.

Chapagain, A.K., Hoekstra, A.Y., 2010. The green, blue and gray water footprint of rice from both a production and consumption perspective. Value of Water Research Report Series No.40. UNESCO-IHE, Netherlands www.waterfootprint.org/Reports/Report40-WaterFootprintRice.pdf.

Chapagain, A.K., Orr, S., 2008. An improved water footprint methodology linking global consumption to local water resources: a case of Spanish tomatoes. J. Environ. Manage. 90 (2), 1219–1228.

Enevoldsen, M.K., Ryelund, A.V., Andersen, M.S., 2007. Decoupling of industrial energy consumption and CO_2 emissions in energy-intensive industries in Scandinavia. Energ. Econ. 29 (4), 665–692.

Environmental Protection Agency (EPA), 2005. List of Drinking Water Contaminants: Ground Water and Drinking Water. US Environmental Protection Agency, Washington, DC, www.epa.gov/safewater/mcl.html#1.

Falkenmark, M., 1995. Land-water linkages: a synopsis//Land and water integration and river basin management. Proceedings of an FAO Informal Workshop. FAO 1, 15–16.

FAO, 2010. CROPWAT 8.0 model. FAO, Rome http://www.fao.org/nr/water/infores-databases-cropwat.html

Graham, J., 2006. Integrating blue and green water flows for water resources management and planning. Phys. Chem. Earth 31 (15–16), 753–762.

Han, X., Wang, S., Song, C., Qiao, Y., 2003. Fate of fertilizer nitrogen in paddy field of black soil region. Chinese J. Appl. Ecol. 14 (11), 1859–1862.

He, X., Wen, A., Zhang, X., Zhu, B., 2005. Decoupled index system of soil erosion in agricultural ecological environment evaluation. J. Soil 42 (5), 852–856.

Hoekstra, A.Y., 2003. Virtual water trade. Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series No 12, UNESCO-IHE, Delft, Netherlands, 12–13 December 2002 www.waterfootprint.org/Reports/Report12.pdf.

Hoekstra, A.Y., Chapagain, A.K., 2008. Globalization of Water: Sharing the Planet's Freshwater Resources. Blackwell Publishing, Oxford, UK.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual – Setting the Global Standard. Earthscan, London, Washington, DC.

Hoekstra, A.Y., Hung, P.Q., 2002. Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series No 11. UNESCO-IHE, Delft, Netherlands www.waterfootprint.org/Reports/Report11.pdf.

Hoekstra, A.Y., Hung, P.Q., 2005. Globalization of water resources: international virtual water flows in relation to crop trade. Global Environ. Change 15 (1), 45–56.

Hoekstra, A.Y., 2013. Sustainable, efficient, and equitable water use: the three pillars under wise freshwater allocation. WIREs Water 2013, http://dx.doi.org/10.1002/wat2.1000.

Jarmo, V., Jyrki, L., Jari, K., 2007. Linking analyses and environmental Kuznets curves for aggregated material flows in the. Eur. J. Clean. Prod. 15 (5), 1662–1673.

Liu, Z., Xia, G., Zhao, Y., 2006. Influence on ecological process of groundwater exploitation in Sanjiang plain. Res. Water Resour. Devlop. 12, 38–41.

Lu, I.J., Lin, S.J., Lewis, C., 2007. Position and decoupling effects of carbon dioxide emission from highway transportation in Taiwan, Germany, Japan and South Korea. Energ. Policy 35 (6), 3226–3235.

Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and gray water footprint of crops and derived crop products. Hydrol. Earth Syst. Sc. 15, 1577–1600.

Massimiliano, M., Roberto, Z., 2008. Waste generation, waste disposal and policy effectiveness evidence on decoupling from the European Union. Resour. Conserv. Recy. 52 (10), 1221–1234.

Mazzanti, M., 2008. Is waste generation de-linking from economic growth? Appl. Econ. Lett. 15 (4), 287–291.

Monireh, F., Karim, C.A., Rainer, S., Hong, Y., 2009. Modelling blue and green water resources availability in Iran. Hydrol. Process 23 (3), 486–501.

OECD,2002. Indicators to Measure Decoupling of Environmental Pressure from Economic Growth. OECD, Paris, pp. 1–3.

OECD,2003. Environmental Indicators—Development, Measurement and Use. OECD, Paris, pp. 1–37.

Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transport Policy 12 (2), 137–151.

UNEP,2011. Decoupling natural resource use and environmental impacts from economic growth. A Report of the Working Group on Decoupling to the International Resource Panel. UNEP, Nairobi, pp. 1–174.

Wu, H., Gu, S., Zhou, H., Wang, X., Dong, D., Hu, Y., 2011. Relationship between energy consumption-carbon emissions and economic growth in Hebei province. Resource Science 33 (10), 1897–1905.

Xu, W., Zhang, J., Li, S., Sun, X., 2010. Decoupling research on relationship between chemical fertilizer usage from crop production in the cyclic agriculture in China. Agric. Modern Res. 31 (2), 200–203.

Yu, F., 2008. Decoupling irrigation water from crop production in China. Chinese Rural Econ. 10, 33–34.

Zeng, Z., Liu, J., Koeneman, P.H., Zarate, E., Hoekstra, A.Y., 2012. Assessing water footprint at river basin level: a case study for the Heihe River Basin in northeast China. Hydrol. Earth Syst. Sc. 16, 2771–2781.

Zhong, T., Huang, X., Han, L., Wang, B., 2010. Review on the research of decoupling analysis in the field of environments and resource. J. Nat. Resource 25 (8), 1400–1412.

Zhang, Z., Zhai, R., Wang, G., 2000. Yield improvement of fertilizer application in the Sanjiang Plain. J. HLR Univ. 12 (3), 1–5.

Zhang, S., Wang, J., Zhang, W., Wang, L., Ma, W., Zhang, F., 2007. The status and problems of fertilizer consumption and production and the strategy for management in Northeast China. Phosphate Compound 22 (5), 74–78.