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我国西北地区主要农作物贸易对区域水资源影响

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摘要:随着我国粮食生产重心的北移,西北地区在全国粮食安全中的作用日益凸显,然而该地区水资源缺乏,水土资源时空匹配性差对当地的生态安全、粮食安全和水安全构成了巨大威胁。近些年,伴随着城市化和区域贸易的快速发展,西北地区农作物产量和外运量均快速增长,大量的农作物虚拟水伴随贸易输送到全国各地,进一步加剧了西北地区的水资源压力,严重制约当地的可持续发展。基于此,本研究对2000—2015年西北地区主要农作物生产水足迹和伴随着农产品贸易的虚拟水流动格局进行了量化分析,在此基础上评估了西北地区农产品贸易输出引发的水资源压力。结果表明,研究期内2000—2015年西北地区主要农作物生产水足迹呈上升趋势,从2000年的417.16亿 m^3 增长到2015年的439.87亿 m^3。与此同时,农产品贸易伴生的虚拟水流动量显著增加,从2000年的220亿 m^3 增长到2015年的272.99亿 m^3,严重加剧了当地的水资源压力。陕西、内蒙古、新疆和甘肃水资源压力均高于全国平均水平,陕西更是呈重度水资源压力状态。因此,本文从技术发展和宏观战略层面提出了创新农业实体水资源利用效率、建立虚拟水补偿机制以及合理优化调整区域产业结构的应对策略与建议,为保障我国西北地区水资源可持续利用提供了科学参考。

关键词:水足迹;虚拟水;可持续性评价;西北地区;作物生产

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水和粮食是人类生存和社会发展所必须的重要物质基础,也是当前社会可持续发展的重要保障[1-2]。在气候变化和人口快速增长的背景下,未来30年我国仍面临粮食新增需求的巨大压力,农业作为我国第一用水大户,其占总用水量的比例超过60%,农业用水的短缺将直接影响我国粮食安全[3]。可以说粮食安全、水安全已成为当今我国乃至全球经济社会可持续发展面临的重大战略性问题,也是我国实现"两个一百年"奋斗目标的重要制约因素。伴随区域间农作物产品贸易量的不断增大,农产品贸易导致的区域间虚拟形态水资源贸易量越来越大,传统的单纯考虑实体水资源的水管理理念表现出较大的局限性,虚拟水的概念由此而产生并以贸易形势将水与粮食连接起来[4-5]。我国农产品贸易由缺水地区向富水地区流动,伴随农产品大规模流出将加剧我国农业主产区水资源稀缺程度[6]。虚拟水作为凝结在产品和服务中的水资源量,以其独特的视角对不合理的产业结构和农产品贸易导致的水资源短缺现状及水资源所面临的压力提供了全新的思路[7-8]。同时,水足迹理论作为虚拟水概念的进一步拓展,用来衡量与生产或消费相关的用水量,也为评价区域水资源承载情况、研究虚拟水贸易结构,制定水资源战略提供重要依据[9]。

现阶段随着虚拟水理论的提出,国内外基于虚

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拟水理论在不同尺度上为保障粮食安全开展了大量研究，在全球尺度上，Hoekstra 和 Hung[10]通过计算得出 1995－1999 年间全球农作物的平均虚拟水流动量为 695×10^9 m^3/a，其中排名前三的净虚拟水出口国依次为美国、加拿大和泰国。在国家和区域尺度上，Ercin[11]等计算了 1996－2005 年法国的水足迹，发现 47％的水足迹消费与农产品进口有关。张志强等[12]基于虚拟水理论测算了我国西北四省的水足迹变化；马静等[13]指出虚拟水战略同实体水调水一样对于保障我国干旱缺水地区水资源安全和粮食安全具有重要作用。王玉宝等[14]计算了 2010 年我国粮食生产、消费、调运及生产用水和虚拟水流动情况，定量研究了我国区域间粮食虚拟水流动对区域经济和水资源的影响，并提出了有效解决我国区域虚拟水流动负面效应的关键措施。在虚拟水引入水资源领域后，水资源压力作为评价虚拟水对区域水资源影响的关键指标，基于水足迹和虚拟水贸易等理论对区域水资源压力进行分析成为一种趋势。Falkenmark 和 Widstrand[15]最早采用人均水资源量来衡量水资源的稀缺程度，并提出水资源压力指数（Water Stress Index，WSI）。Ohlsson[16]在 Falkenmark 的研究基础上考虑社会因素，从而得到了社会型水资源压力指数（SWSI）。戚瑞等[17]基于水足迹理论对大连分析考虑了该区域的水资源压力。韩宇平等[18]综合考虑实体水、虚拟水，构建了区域水资源压力状态评价指标体系。赵旭等[19]计算了 2007 年我国各省的实际水资源压力指数和考虑虚拟水流入后的水资源压力指数，研究结果表明，实体水和虚拟水流动会大大加剧水出口地区的水资源压力。

可以发现，伴随作物生产的水资源大量流出将对当地水资源造成不可恢复的影响，基于此，以水足迹及虚拟水视角对西北地区 2000－2015 年水密集性作物产品流动带来的水资源压力进行量化评估，为下一步我国西北地区乃至全国的水、粮食安全保障提供建议。

1 数据与方法

1.1 研究区概况

本文选取西北地区作为研究区，西北地区主要包括我国的陕西，甘肃，宁夏，青海，新疆和内蒙古西部地区，其中内蒙古西部地区包括包头市、鄂尔多斯市、巴彦淖尔市、乌海市以及阿拉善盟，研究区域见图 1。西北地区作为我国主要的粮食生产基地，地域辽阔，国土面积占全国的 35％[20]。与此同时，西北地区又属于我国最为缺水的干旱、半干旱地区，气候干燥，降水量少，水资源量仅占全国的 8％，其中农业用水占西北地区总用水量的 88.5％，农业用水短缺已经成为制约当地经济发展和社会进步的最主要因素[21-22]。基于西北地区水资源缺乏，土地资源、水资源反向分布的现状，本文将西北地区设为研究区。

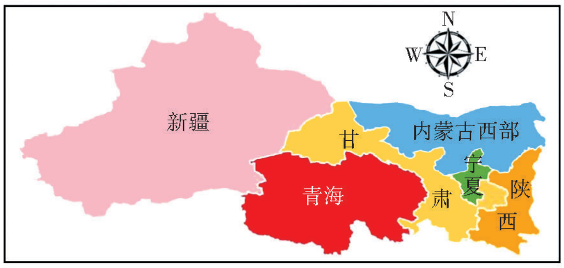

图 1　研究区

1.2 计算方法

1.2.1 农作物虚拟水流动量核算

由于缺乏粮食储存数据，本文在农作物的虚拟水流动计算过程中假设西北各省级行政区当年农产品零库存，生产优先满足本地消费[23]。本文的研究对象主要针对西北地区各省级行政区水密集型农作物产品，见表 1。

表 1　西北地区水密集型农产品

省、自治区	水密集型作物
甘肃	小麦、马铃薯、油料
青海	小麦、马铃薯、油料
内蒙古西部	小麦、玉米
陕西	小麦、玉米、苹果
宁夏	玉米
新疆	棉花

虚拟水流动量计算公式如下：

$$\text{当 } G_i'>0 \qquad V_{W_i}=G_i'W_{F_i}^G \tag{1}$$

$$\text{当 } G_i'<0 \qquad V_{W_i}=G_i'W_{F_o}^G \tag{2}$$

式中：V_{W_i} 为西北地区第 i 省级行政区虚拟水流动量（亿 m^3）；$W_{F_i}^G$ 为西北地区第 i 省级行政区的作物生产水足迹（m^3/kg）；$W_{F_o}^G$ 是作为输出的那部分作物生产水足迹，由西北各农作物输出省区的作物生产水足迹对相应省区的作物输出量的加权得到；G_i' 为西北地区第 i 省级行政区的作物调运量（万 t），当 $G_i'>0$ 时表示输出，当 $G_i'<0$ 时表示输入，当 $G_i'=0$ 时表示无调运。各省级行政区作物调运量的计算公式为

$$G_i'=G_i-P_i\frac{G_N}{P_N} \tag{3}$$

式中：P_N 为全国人口（万人）；G_N 为全国作物总产

量(万 t);G_i 为西北地区第 i 省级行政区的作物生产量(万 t);P_i 为西北地区第 i 省级行政区的人口数量(万人)。

1.2.2 水资源压力指数核算

水资源压力指数(WSI)首先由 Smakhtin 等提出,指从现有的当地水资源中取水而产生的水资源压力。基于现有 WSI 概念,为了更严格地管理区域水资源,表征虚拟水流动对区域水资源的影响,在传统水资源压力的基础上,将水利部最严格水资源管理制度之中的区域用水总量控制指标引入水资源压力指数的计算中,提出了一种修正的水压力指数(MWSI),用以量化由作物输出引起的虚拟水流出对西北地区水资源短缺的影响,计算公式如下[24]:

$$\mathrm{MWSI}=\frac{V_W}{L_Q}\times 100\% \tag{4}$$

$$\mathrm{MWSI}_f=\frac{W}{L_Q}\times 100\% \tag{5}$$

式中:MWSI 为西北地区各省级行政区作物输出引起的水资源压力;V_W 为西北地区各省级行政区伴随作物输出的虚拟水流出量(m^3);L_Q 为"三条红线"水资源控制框架下西北地区各省级行政区可利用水资源的上限(m^3)。MWSI 将水资源短缺程度分为四个等级:无压力($\mathrm{MWSI}\leqslant 0.2\mathrm{MWSI}_f$),轻度压力($0.2\mathrm{MWSI}_f\leqslant \mathrm{MWSI}\leqslant 0.4\mathrm{MWSI}_f$),中度压力($0.4\mathrm{MWSI}_f\leqslant \mathrm{MWSI}\leqslant 0.8\mathrm{MWSI}_f$),重度压力($0.8\mathrm{MWSI}_f<\mathrm{MWSI}\leqslant \mathrm{MWSI}_f$)。其中,$\mathrm{MWSI}_f$ 为西北地区作物生产引起的水资源压力,用式(5)计算,W 为西北地区用于作物生产的用水量(m^3)

1.3 数据来源

1.3.1 作物虚拟水流动数据来源

本研究中西北地区的作物产量和人口数量等数据引自2001—2016年的《中国统计年鉴》[25]。农业用水量等数据引自2001—2015年《中国水资源公报》和《中国水利年鉴》以及西北地区的《水资源公报》。

1.3.2 水资源利用相关数据来源

本研究采用国务院发布的《实行最严格水资源管理制度考核办法》中的区域用水总量控制目标以及2000—2015年西北各省、自治区《水资源公报》中的农业用水量计算水资源压力指数,分析作物生产对当地水资源系统的影响。

2 结果分析

2.1 西北地区作物生产时空分析

西北地区作为我国主要的粮食基地,从2000年到2015年平均生产农作物5 427.95万 t,占全国平均粮食生产总量的8.84%。全区域伴随农作物生产的水足迹从2000年的417.16亿 m^3 增长到2015年的439.87亿 m^3。

本研究具体分析2000—2015年西北地区农作物生产及伴随作物生产过程的水足迹时空变化趋势,见图2。2000—2015年新疆及宁夏农作物产量与水足迹呈增加趋势。新疆农作物产量从145.6万 t(2000年)增加至350.3万 t(2015年),年均增长6.03%;由于新疆主要农作物为棉花且棉花单位水足迹是其他省份作物单位水足迹的4倍左右,导致新疆农作物水足迹随棉花产量增加而不断增大,从2000年的92.56亿 m^3 增长到2015年的162.55亿 m^3,并在2012年之后超过陕西成为西北地区农作物水足迹最高的区域。宁夏农作物产量从82万 t(2000年)增加至226.88万 t(2015年),年均增长7.02%,伴随作物产量增加其水足迹从13.32亿 m^3(2000年)增加至21.24亿 m^3(2015年)。

陕西及甘肃作物产量呈增加趋势,但伴随作物产量增加水足迹呈下降态势。陕西农作物产量从1 220.87万 t(2000年)增加至2 038.48万 t(2015年),同时陕西作为西北地区农作物产量最高的省份,每年平均生产作物1 611.31万 t,占西北地区农作物生产量的57%;甘肃农作物产量从309.53万 t(2000年)增加至405.67万 t(2015年)年均增幅很小,仅为1.81% 然而,由于农业用水技术进步和管理水平的提高,2000—2015年甘肃及陕西作物生产单位水足迹逐年下降,导致陕西及甘肃作物水足迹分别从183.92亿 m^3 和88.99亿 m^3(2000年)降低到144.94亿 m^3 和76.73亿 m^3(2015年)。

2000—2015年,青海省农作物产量与水足迹呈先增加再下降趋势,作物产量及伴随作物生产的水足迹分别从2000年的78.2万 t 和10.89亿 m^3 增加至2009年的113.94万 t 和12.04亿 m^3 再下降至2015年的99.4万 t 和10.63亿 m^3;内蒙古西部地区农作物产量呈增加趋势,作物产量从229.95万 t(2000年)增加至462.32万 t(2015年),伴随农作物产量增加,内蒙古西部地区作物水足迹在2000—2009年呈增加态势,但由于工农业技术和设备的革新以及管理模式的不断进步,2009年之后作物生产单位水足迹下降。

2.2 西北地区伴随农作物外送的虚拟水流动分析

由于西北地区农作物生产量远超本地对于农作

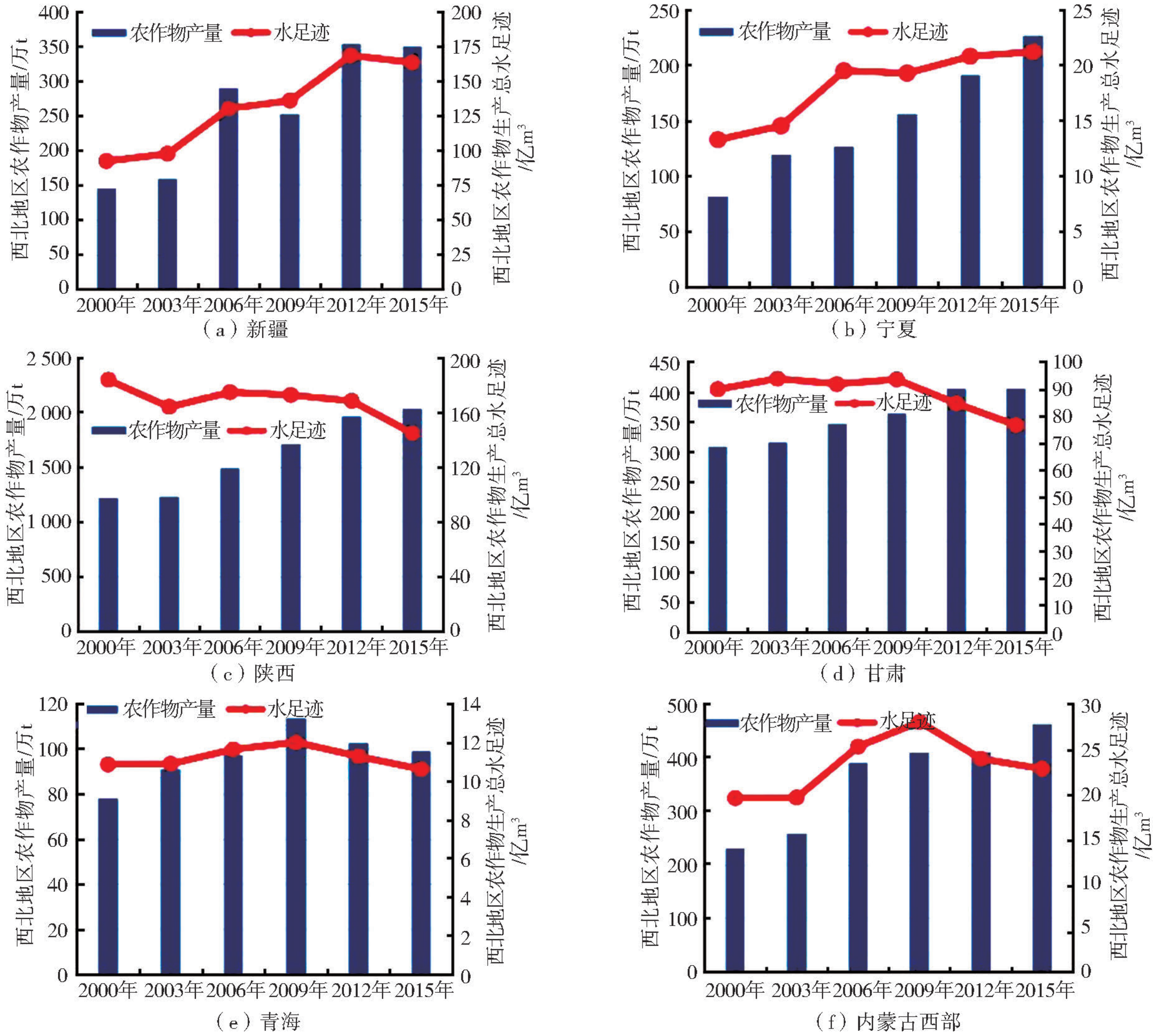

图 2　2000—2015 年西北地区各省农作物产量及水足迹变化趋势

物的需求量，大量农作物向外流出。2000—2015 年伴随农作物的大规模流出西北地区虚拟水流动量年均达 254.6 亿 m³，西北地区虚拟水流动量变化趋势及虚拟水输出比分别见图 3、图 4。

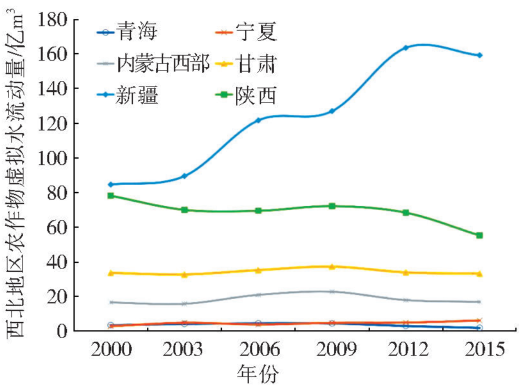

图 3　2000—2015 年西北地区各省、自治区农作物虚拟水流动量变化趋势

伴随农作物贸易西北各省、自治区农作物虚拟水流动量在年际上呈现不同的变化趋势。新疆和陕西由于大量的农作物输出虚拟水流动量极大，分别

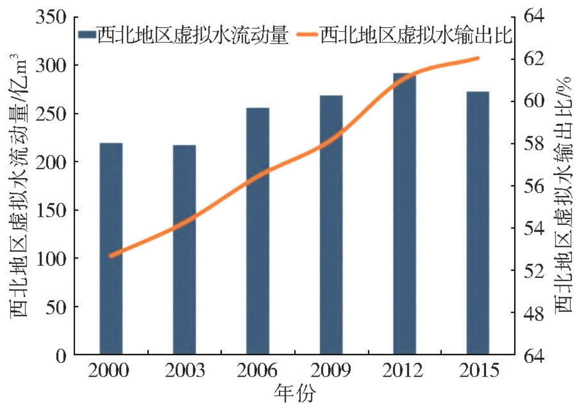

图 4　2000—2015 年西北地区作物虚拟水流动量及输出比变化趋势

占到西北地区虚拟水总流出量的 48% 和 28%。其中由于新疆的本地棉花消耗量极小，大量棉花向外输送，外送量达到本地生产量的 96.2% 左右，导致当地虚拟水输出比达 94%，新疆虚拟水流动量逐年攀升从 84.62 亿 m³（2000 年）增长到 159.17 亿 m³（2015 年）；陕西作为我国西北地区主要农作物产业

基地，多年平均农作物输出比达 47.74%，伴随农作物输出的虚拟水输出比达 40.9%。但伴随农业用水管理水平和技术的提高，陕西作物生产单位水足迹逐年下降，致使陕西虚拟水流动量呈下降趋势，从 2000 年的 78.21 亿 m^3 下降至 2015 年的 55.3 亿 m^3；其余省、自治区虚拟水流动年际变化稳定。

2000—2015 年，西北地区虚拟水流动量呈增加趋势，从 2000 年的 219.81 亿 m^3 增长到 2015 年的 272.99 亿 m^3，增长率达到 24%。此外，西北地区作为我国重要的粮食基地，虚拟水输出比（虚拟水/水足迹）逐年增加，从 52.69%（2000 年）增加至 62.06%（2015 年），充分说明大量农作物生产主要用于向外输出而非本地使用，据统计 2000 年，西北地区作物虚拟水流动量为 219.81 亿 m^3，占西北地区作物总用水量的 57.3%；2015 年西北地区作物虚拟水流动量为 272.99 亿 m^3，占西北地区作物总用水量的 65.8%。可以发现，西北地区伴随作物输出的虚拟水流动将加剧西北地区本就匮乏的水资源压力。

2.3 西北地区伴随农作物虚拟水流动的水资源压力

随着我国社会经济的不断发展，近年来对农作物的需求量持续性增加，西北地区作为重要的粮食基地生产规模逐渐扩大，伴随农作物外调虚拟水流出量不断攀升，进而对西北地区水安全问题造成了严重威胁。基于提出的 MWSI 计算方法对西北地区年际变化下的 MWSI 进行了计算，见图 5、表 2。

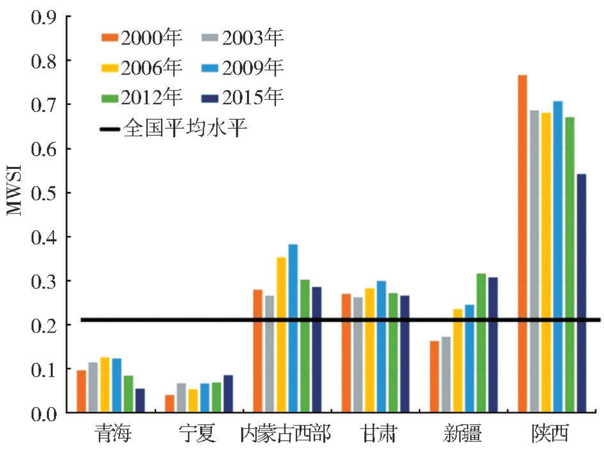

图 5 2000—2015 年西北地区伴随作物虚拟水流动的水资源压力

伴随农作物的贸易，西北地区大量的水资源以虚拟水的形式输出到全国各地，给当地带来严峻水资源压力。可以发现，青海、宁夏由于作物产量及贸易量少，当地的水资源量基本可以支撑其作物生产，因此处于无压力状态。而其余省、自治区水资源压力均高于全国平均水平。内蒙古西部地区以及甘肃 2000—2015 年一直处于轻度压力的状态，而新疆在 2006 年之前水资源压力一直处于无压力状态，但随着当地作物产量的不断攀升其水资源压力上升到轻度压力状态。陕西由于 2012—2015 年单产水足迹降低，导致其水资源压力由极重压力降至重度压力，但陕西省目前仍面临十分严重的水资源压力问题，其水资源压力远高于全国水平。总的来看，西北地区农作物的生产与调运给当地用水安全带来了巨大的风险，水资源可持续性利用受到制约。

表 2 2000—2015 年西北各省水资源压力程度

省、自治区	水资源压力程度					
	2002年	2003年	2006年	2009年	2012年	2015年
青海	无	轻度	轻度	轻度	无	无
宁夏	无	无	无	无	无	无
内蒙古四部	轻度	轻度	轻度	轻度	轻度	轻度
甘肃	轻度	轻度	轻度	轻度	轻度	轻度
新疆	无	无	轻度	轻度	轻度	轻度
陕西	极重	极重	极重	极重	极重	重

然而，伴随"十三五"规划以及西部大开发战略的不断推进，西北地区在未来将面临更大程度的水资源压力。大量虚拟水伴随作物输出外流使得西北地区本就匮乏的水资源在未来无法继续支撑当地作物生产。此外，当地的生态和环境压力也远远超过了其承载能力，必将影响西北地区生态环境和水资源可持续发展，对我国作物安全造成威胁，因而采取相应政策缓解当地水资源压力问题尤为重要。

2.4 西北地区作物虚拟水流动伴生的经济影响

通过对比西北地区三大产业单方水经济效益，见表 3。可以发现，农作物产品作为高耗水低收益产品，其相对于工业及第三产业的经济收益较低，对于西北地区而言以工业用水以及第三产业单方水经济效益达到农业单方水经济效益的 30 到 40 倍左右。同时，西北地区作为作物虚拟水净输出区大量水资源用于作物生产，由于农业相较于其他产业附

表 3 2015 年西北地区三大产业单方水经济效益

元

省、自治区	农业	工业	第三产业
青海	10.15	308.23	333.60
宁夏	4.07	222.66	344.90
内蒙古西部	11.73	411.66	268.16
甘肃	10.35	153.28	293.11
新疆	2.93	232.26	219.44
陕西	28.90	517.23	384.40

加值低，西北地区相当于放弃了水资源的更高的机会成本来生产农作物产品，长此以往导致其在经济收益上与虚拟水输入区存在较大差异，严重制约当地经济发展和城市化工业化进程，更是进一步加剧区域间的不均衡，造成经济不发达和水资源匮乏地区经济发展更加滞后，水、粮食安全问题更加突出的恶性循环。

3 结论与建议

本研究以虚拟水视角看待水安全及粮食安全问题，基于虚拟水及水足迹理论，以水资源压力为落脚点，重点研究2000至2015年间我国西北地区主要农作物的生产与贸易过程，从水足迹、虚拟水视角分析了伴随农产品贸易的虚拟水流动情况以及对当地水资源可持续利用造成的水资源压力，并取得如下结论。

(1)我国西北各省、自治区农作物生产及伴随作物生产过程的水足迹在时空上存在不同变化趋势，新疆及宁夏农作物产量与水足迹均呈增加趋势；陕西及甘肃作物产量呈增加趋势，但伴随作物产量增加水足迹呈下降态势；青海农作物产量与水足迹均呈先增加再下降趋势；内蒙古西部地区农作物产量呈增加趋势，但伴随农作物产量增加，由于工农业技术和设备的革新以及管理模式的不断进步，内蒙古西部地区作物水足迹在2000－2009年呈增加态势，2009－2015年呈下降态势。对于全区域而言，西北地区作物产量增长，全区域农作物生产水足迹从2000年的417.16亿m^3增长到2015年的439.87亿m^3。

(2)西北地区农产品贸易输出量逐年增长，伴生的农产品虚拟水流动量亦逐年增加。据测算，区域作物虚拟水流动量从219.81亿m^3(2000年)增加到272.99亿m^3(2015年)，增幅达24%。同时，西北地区虚拟水输出比逐年增加，2000年虚拟水输出比为52.69%，2015年增至62.06%。

(3)伴随农产品输出的虚拟水流动无疑将会加剧西北地区的水资源矛盾。内蒙古、新疆和甘肃水资源压力高于全国平均水资源压力呈轻度水资源压力状态，陕西则呈重度水资源压力状态。西北地区未来将面临十分严重的水资源短缺问题。

西北地区作为我国重要的粮食产区，近些年，伴随着农产品的贸易外运，区域内大量的水资源以虚拟水的形式输出到全国各地，进一步加剧了该地区的水资源供需矛盾。为保障区域未来的水安全、粮食安全和生态安全，应实现区域实体水－虚拟水统筹管理，因此本文提出如下应对措施和建议。(1)依靠科技创新，提升农业实体水资源利用效率。继续加大高产育种和节水农业技术研究，提高区域水资源的动态监测和预报能力，推进农田高效节水工程建设，通过技术手段和工程手段，提升作物单产，降低灌溉用水损耗，提高农田水分利用水平，实现有限水资源的高效利用。(2)依靠管理杠杆，建立虚拟水补偿机制。为保障西北地区社会经济和生态系统的可持续发展，建议从国家层面建立针对农产品输出的虚拟水补偿机制。在该机制框架内，虚拟水输入区每年通过一定的计算规则向国家上缴虚拟水水费或虚拟水补偿费，国家又通过一定的方式将专项费用返还给虚拟水输出区用以实施节水改造、生态修复、水资源开发保护等工程，从而调动虚拟水输出区的积极性，促进区域经济的均衡可持续发展。(3)依靠系统优化，合理调整区域产业结构。当前，建立适水型产业结构是应对社会经济发展水资源约束的有效途径。针对西北缺水地区，应深入分析现有产业结构与当地水资源承载力的匹配条件，建立与当地资源条件、区位优势和经济发展相适应的产业结构，合理压缩农业生产规模是保障该地区经济增长、生态健康和社会可持续发展的关键。

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·译文·

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Analysis of the impact of major crop trade on regional water resources in Northwest China

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Abstract: With the shift of China's food production centre to the north, Northwest China plays an prominent role in the national food security. However, the lack of water resources and the poor spatial and temporal compatibility of water and soil resources pose a huge threat to the local ecological security, food security, and water security in this region. In recent years, grain production and transport volume in Northwest China has been increasing rapidly due to prompt development of urbanization and regional trade. A large amount of crop virtual water has been transported to all over the country along with the grain trade, which has further exacerbated the pressure on water resources and seriously restricts the sustainable development in northwest region of China. Based on above scenario, this study conducted a quantitative analysis of water footprint and virtual water flow pattern accompanied by agricultural product's trade in Northwest China from 2000 to 2015. Besides, the water resource pressure caused by agricultural product's trade in Northwest China was also assessed. The results shows that during the study period from 2000 to 2015, the water footprint of major crops in Northwest China appeared in an upward trend, from 41.716 billion m^3 in 2000 to 43.987 billion m^3 in 2015. Moreover, the virtual water flow associated with agricultural product's trade significantly increased, which was between 22 billion m^3 (2000) to 27.29 billion m^3 (2015), with an increased rate of 24%. Consequently, local water resource pressure was severe. The water resource pressure of Shaanxi, Inner Mongolia, Xinjiang and Gansu was higher than the national average water resource pressure, while Shaanxi was in a state of severe water resource stress. Therefore, this paper proposed coping strategies and suggestions on technological development for innovative agricultural entity water resources utilization efficiency, and rationally optimizing and adjusting regional industrial structure, to provide scientific reference for ensuring sustainable utilization of water resources in Northwest China.

Key words: water footprint; virtual water; sustainability assessment; Northwest; crop production

Water and food are important material basis for human survival and social development, and also an important guarantee for sustainable development of the current society[1-2]. In the context of climate change and rapid population growth, China will still face great pressure on food demand in the next 30 years. Agriculture, as China's largest water user, accounts for more than 60% of total

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water consumption. The shortage of agricultural water will directly affect China's food security[3]. It can be said that food security and water security have become the major strategic issues facingby China and even the world for the sustainable economic and social development. They are also essential constraints for China to achieve" the two centenary goals" . fWith the increasing trade volume of regional agricultural products, the trade volume of regional virtual water resources caused is also increasing. The traditional water management concept that only considers the real water resources shows great limitations. The concept of virtual water arises from this and connects water and food with the trade situation[4-5]. China's agricultural products trade lows from the water-deficient area to the water-rich area. The large-scale outflow of agricultural products will aggravate the scarcity of water resources in China's leading agricultural production areas. Virtual water, as the amount of water condensed in products and services, provides a new idea from its unique perspective on the current situation of water shortage and water pressure caused by unreasonable industrial structure and agricultural trade[7-8]. Simultaneously, the water footprint theory is a further expansion of the concept of virtual water. This theory is used to measure the water consumption related to production. Besides, it may also provides an important basis for evaluating regional water resource carrying capacity, studying the structure of virtual water trade and formulating water resource strategy[9].

Presently, with the development of virtual water theory, several studies have been carried out all over the world to guarantee food securityat different scales . For example, Hoekstra and Hung[10] calculated that the average virtual water flow of global crops from 1995 to 1999. The results of his study exhibited that the average virtual flow was 695×10^{9} m^{3}/a, among which the top three net virtual water exporters were the United States, Canada and Thailand. Ercin et al.[11] calculated the water footprint of France from 1996 to 2005. They found that 47% of the water footprint consumption was related to the import of agricultural products. Zhang Zhiqiang et al.[12] calculated the changes in the water footprint in four provinces of Northwest China based on the virtual water theory. Ma Jing et al.[13] pointed out that the virtual water strategy played an important role in ensuring water resources security and food security in China's arid and water-deficient areas just like the real water diversion strategy. Wang Yubao et al.[14] calculated the virtual water for China's food production, consumption and transportation in 2010. Auhtor studied the quantitative impact of China's interregional virtual water flow of food on regional economy and water resources and proposed key measures to effectively solve the negative effects of China's regional virtual water flow. Moreover, water resource pressure is a key index to evaluate the impact of virtual water on regional water resources. The water resource pressure has become a trend to analyze regional water resource pressure based on water footprint and virtual water trade theories. For instance, Falkenmark and Widstrand[15] used average per capita water resources to measure the water resources scarcity degree and proposed Water Stress Index (WSI). Ohlsson[16] studied the social water stress index (SWSI) by considering social factors on the basis of Falkenmark's research. Qi Rui et al.[17] analyzed the water resource pressure in Dalian, China based on the water footprint theory. Han Yuping[18] developed a regional water resource pressure evaluation index system by comprehensively considering the real water and virtual water. Zhao Xu et al.[19] calculated the actual water resource pressure index by taking into account of the inflow of virtual water in each province of China in 2007. The studies shows that the water resource pressure of water outlet areas would be greatly aggravated by the flow of real water and virtual water.

It can be found that the large outflow of water resources associated with crop production, and will have an irreversible impact on local water resources. Based on this, we conducted a quantitative assessment of water resource pressure caused by water-intensive crop product flow from the perspective of water footprint and virtual water in Northwest China from 2000 to 2015. We also provided suggestions for water and food security in Northwest China and for the whole country as well.

1 Material and methods

1.1 Study area

Northwest China was selected as the research area because of lack of water resources and the reverse distribution of land resources and water resources. The Northwest China mainly comprised Shaanxi, Gansu, Ningxia, Qinghai, Xinjiang and the western region of Inner Mongolia including Baotou City, Ordos City, Bayan Nur City, Wuhai City and Alxa League (Fig. 1). The northwest region is a main food production bases of China and has a vast territory, accounting for 35% of the national land area[20]. The Northwest China has arid and semi-arid areas with a dry climate and little precipitation and the most water shortage region in China. The amount of water resources accounts for 8% of the whole country, among which agricultural water accounts for 88.5% of the total water consumption in Northwest China. Agricultural water shortage has become the most essential factor restricting local economic development and social progress[21-22].

Fig. 1 Location of research area

1.2 Methods

1.2.1 Crop virtual water flow accounting

Due to the lack of grain storage data, this paper assumed that the Northwest Provinces have zero agricultural products in the current year in the calculation of the virtual water flow of the crops, and the production was preferred to meet the local consumption[23]. The research object of this paper mainly focused on water-intensive crop products in the Provinces of Northwest China (Tab. 1).

Tab. 1 Water intensive agricultural products in Northwest China

Province or Autonomous Region	Water intensive crops
Gansu	Wheat, Potatoes, Oil
Qinghai	Wheat, Potatoes, Oil
Western Inner Mongolia	Wheat, Corn
Shaanxi	Wheat, Corn, Apples
Ningxia	Corn
Xinjiang	Cotton

The formula for the calculation of virtual flow was as follows:

$$\text{When } G_i'>0 \quad V_{W_i}=G_i'W_{F_i}^G \tag{1}$$

$$\text{When } G_i'<0 \quad V_{W_i}=G_i'W_{F_o}^G \tag{2}$$

where: V_{W_i} was the momentum of virtual water flow in the ith provincial administrative region of Northwest China (10^8 m^3); $W_{F_i}^G$ was the water footprint of crop production in the ith provincial administrative region of Northwest China (m^3/kg); $W_{F_o}^G$ was the part of crop production water footprint in output, which was obtained by weighting the crop production water footprint of each crop output province in Northwest China to the crop output of the corresponding province; G_i' was the crop transfer of the ith provincial administrative region in Northwest China (10^4 t). When $G_i'>0$, it represented the output, when $G_i'<0$, it represented the input, when $G_i'=0$, it represented without dispatching. The transport volume in each provincial administrative region can be calculated as follows

$$G_i'=G_i-P_i\frac{G_N}{P_N} \tag{3}$$

where: P_N was the national population (10^4 people); G_N was the total crop production of the country, 10^4 t; G_i was the crop production of the ith provincial administrative region in Northwest China, 10^4 t; P_i was the population of the ith provincial administrative region in Northwest China (10^4 people).

1.2.2 Water stress index calculation

Water resource stress index (WSI) was first proposed by Smakhtin et al. WSI refered to the water resource pressure caused by water taking from existing local water resources. In order to strictly manage regional water resources, the influence of virtual water flow on regional water resources was characterized. The regional total water consumption control index in the strict water resource management system of the Ministry of Water Resources was introduced to calculate the water resource pressure index on the basis of traditional water pressure. Finally, a modified water stress index (MWSI) was proposed to quantify the impact of virtual water outflow caused by water shortage for crop output on in Northwest China. The calculation formula is as follows[24]:

$$\mathrm{MWSI}=\frac{V_W}{L_Q}\times 100\% \quad (4)$$

$$\mathrm{MWSI}_f=\frac{W}{L_Q}\times 100\% \quad (5)$$

where: MWSI was the water resource pressure caused by crop export in northwest provinces. V_W was the amount of virtual water flow that accompanies crop output in each province of Northwest China (m^3); L_Q was the upper limit of available water resources in each province of Northwest China under the "three red lines" water resources control framework (m^3); MWSI divided the water shortage degree into four levels: no pressure ($\mathrm{MWSI} \leqslant 0.2\mathrm{MWSI}_f$), mild pressure ($0.2\mathrm{MWSI}_f \leqslant \mathrm{MWSI} \leqslant 0.4\mathrm{MWSI}_f$), moderate pressure ($0.4\mathrm{MWSI}_f \leqslant \mathrm{MWSI} \leqslant 0.8\mathrm{MWSI}_f$) and severe pressure ($0.8\mathrm{MWSI}_f < \mathrm{MWSI} \leqslant \mathrm{MWSI}_f$). where, MWSI_f was the water resource pressure caused by crop production in Northwest China. The equation (5) was used to calculate MWSI_f. W was the water consumption for crop production in Northwest China (m^3).

1.3 Data

1.3.1 The data sources for crops virtual water flow

Crop yield and population in Northwest China were obtained from《China Statistical Yearbook》from 2001 to 2016[25]. Agricultural water consumption and other data were extracted from《China Water Resources Bulletin》and《China Water Conservancy Yearbook》and《Water Resources Bulletin of Northwest China》from 2001 to 2015.

1.3.2 The data sources related to water resource utilization

The regional total water consumption control target from the "implementing the strict water resource management system assessment methods" issued by the State Council and the agricultural water consumption from the "water resources bulletin" of Northwest Provinces and Autonomous Region from 2000 to 2015 were used to calculate the water resource pressure index and analyzed the impact of crop production on the local water resource system.

2 Results and analysis

2.1 Spatiotemporal analysis of crop production in the Northwest China

As China's main grain base, Northwest China produced 54.28 million tons of grain on an average from 2000 to 2015, accounting for 8.84 percent of the national average grain production. The regional water footprint with crop production increased from 41.72 billion m^3 in 2000 to 43.989 billion m^3 in 2015.

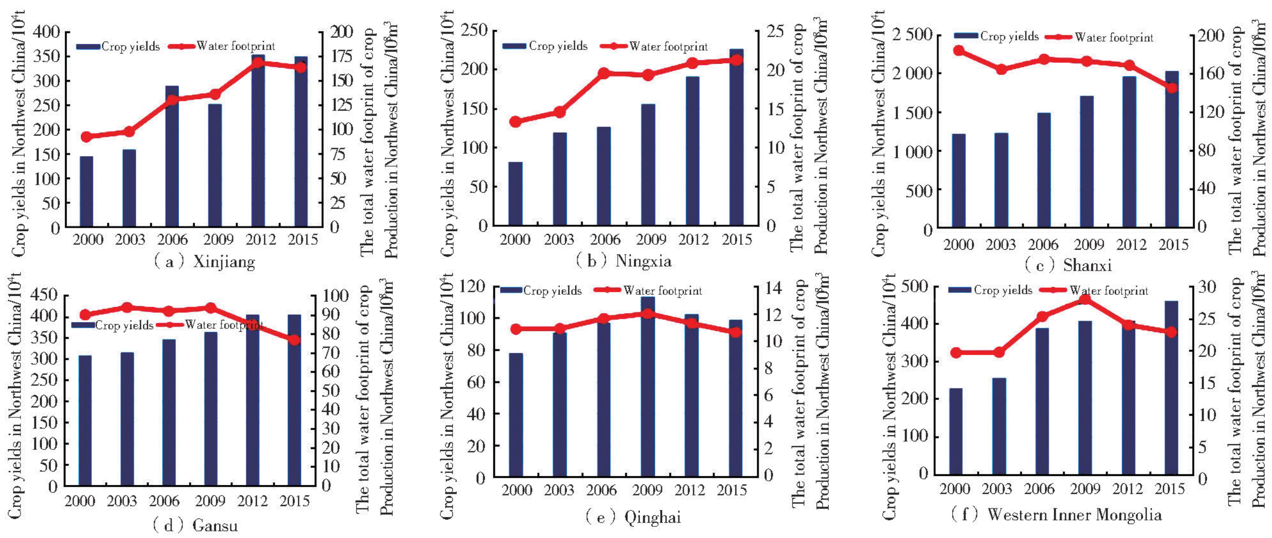

Fig. 2 Trend of crop yield and water footprint in Northwest China from 2000 to 2015

Analyzed the temporal and spatial variation trend of crop production and the water footprint associated with crop production process in Northwest China from 2000 to 2015 (Fig. 2). In these years, crop yield and water footprint increased in Xinjiang and Ningxia. The crop yield of Xinjiang increased from 1.455 6 million tons (2000) to 3.503 million tons (2015), with an average annual growth rate of 6.03%. The cotton crop is a main crop in Xinjiang and the cotton's unit water footprint was about 4 times compared to other. The water footprint of crops in Xinjiang increased with the increase of cotton production, which was ranged between 9.256 billion m^3 in 2000 to 16.255 billion m^3 in 2015, respectively, and surpassed Shaanxi to become a region with the highest water footprint of crops in Northwest China after the year 2012. The crop yield of Ningxia increased from 820 000 tons (2000) to 2 268 800 tons (2015), with an average annual growth of 7.02%. With the increase of crop yield, its water footprint increased from 1.332 billion m^3 (2000) to 2.124 billion m^3 (2015), respectively.

The crop yield in Shaanxi and Gansu increased, but the water footprint decreased with the increase of crop yield. The crop output of Shaanxi Province increased from 12.208 7 million ton (2000) to 20.384 8 million ton (2015). Moreover, Shaanxi is a highest crop output Provice in Northwest China, produced 16.131 million ton of crop on an average per year, accounting for 57% of the crop output in Northwest China. The crop yield of Gansu increased from 3.095 3 million ton (2000) to 4.056 7 million ton (2015), the average annual growth was very small (1.18%). However, advances in agricultural water technology and the improvement of management level, the unit water footprint of crop production in Gansu and Shaanxi decreased every year during 2000 to 2015. In the past 15 years, the water footprint of crops in Shaanxi and Gansu showed a steady decline trend which was from 18.392 billion m^3 and 8.899 billion m^3 (2000) to 14.494 billion m^3 and 7.673 billion m^3 (2015), respectively.

The crop yield and water footprint of Qinghai increased first and then decreased from 2000 to 2015. The crop yield and water footprint of crop production increased from 782 000 tons and 1 089 million m^3 in 2000 to 1,139 400 tons and 1 204 million m^3 in 2009, respectively, and decreased to 994 000 tons and 1 063 million m^3 in 2015. The crop yield in Western Inner Mongolia was increasing, which was from 2.299 5 million ton (2000) to 4.623 2 million ton (2015). The water footprint of crops in Western Inner Mongolia increased from 2000 to 2009, but due to the innovation of industrial and agricultural technology, equipment and the continuous progress of management model, the unit water footprint of crop production decreased after 2009.

2.2 Analysis of virtual water flow with crop delivery in Northwest China

As crop production in Northwest China far exceeds local demand for crops, a large number of crops have been exported. From 2000 to 2015, with the large scale outflow of crops, the annual average amount of virtual water flow in Northwest China reached 25.46 billion m^3. The trend of the momentum of virtual water flowing and the output ratio of virtual water in Northwest China are shown in Fig. 3 and 4, respectively.

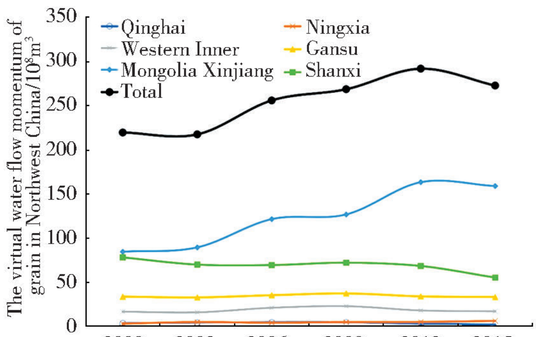

Fig. 3 Trends of crop yield virtual water flow in Northwest China from 2000 to 2015

Along with crop trade, the virtual flow momentum of crops in the Northwest Provinces or Autonomous Regions presented different changing trends every year. The virtual water flow in Xinjiang and Shaanxi accounts for 48% and 28% of the total virtual water outflow in Northwest China due to a large number of crop output. The local cotton consumption in Xinjiang was minimal, and a large amount of cotton was transported outlde, which reached about 96.2% of the domestic production, resulting in the local virtual water output ratio reaching 94%. The virtual water flow momentum in Xinjiang increased every year, from 8.462 billion m^3 (2000) to 15.917 billion m^3 (2015). As a main crop industry base in Northwest China, Shaanxi has an annual average crop output ratio of 47.74%, and the virtual water output ratio accompanying the crop output reached up to 40.9%. However, with the improvement of agricultural water management level and technology, the unit water footprint of crop production in Shaanxi decreasedg was year by year, resulting in a declining trend of the virtual water flow momentum in Shaanxi, which was from 7.821 billion m in 2000 to 5.53 billion m in 2015, respectively. The annual variation of virtual water flow in other provinces and autonomous region was stable.

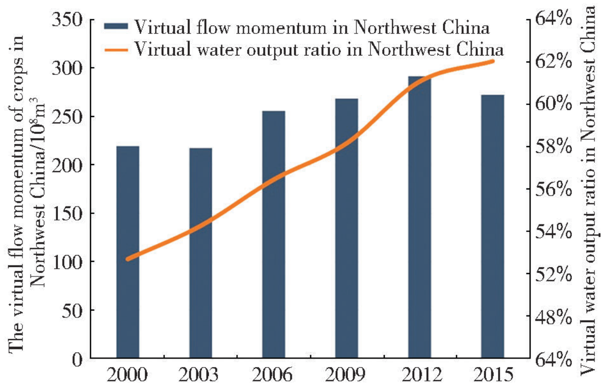

Fig. 4 Virtual water output ratio of food in Northwest China from 2000 to 2015

From 2000 to 2015, the momentum of virtual water flow in Northwest China increased from 21.981 billion m^3 (2000) to 27.299 billion m^3 (2015), with a growth rate of 24%. In addition, the northwest region as the important grain base in China, the virtual water output ratio (virtual water/water footprint) was increasety year by year. The increase was ranged from 52.69% (2000) to 62.06% (2015).

Overall, it showed that a large number of crops were mainly used for export rather than local use. According to statistics, the virtual flow momentum of crops in Northwest China was 21.981 billion m^3 in 2000, accounting for 57.3% of the total crop water consumption in Northwest China. In 2015, the virtual flow momentum of crops in Northwest China was 27.299 billion m^3, accounting for 65.8% of the total crop water consumption in Northwest China. It can be found that the virtual water flow accompanying crop output in Northwestern China will intensify the pressure of water resources in Northwest China.

2.3 Water resources pressure with the virtual water flow of crops in Northwest China

In recent years, the demand of crops has been increasing continuously due to the continuous development of China's society and economy. As an important grain base, the production scale in Northwest China has been gradually expanded, and the virtual water flow volume has been increasing with the transfer of crops, thus posing a severe threat to water security in Northwest China. Based on the proposed MWSI calculation method, we calculated the MWSI under the interannual variation in the northwest region, as shown in Fig. 5 and Tab. 2.

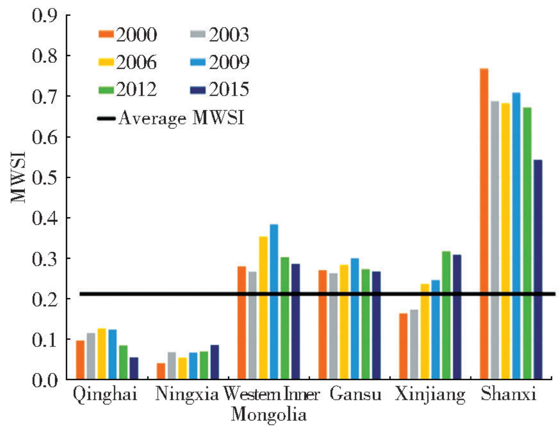

Fig. 5 Water resource pressure associated with virtual water outflow of food in Northwest China from 2000 to 2015

Tab. 2 Degree of water stress in Northwest China from 2000 to 2015

Province, Autonomous Region	Prwinoes ongd Autonomos Region					
	2000	2003	2006	2009	2012	2015
Qinghai	No	Mild	Mild	Mild	No	No
Ningxia	No	No	No	No	No	No
Western Inner	Mild	Mild	Mild	Mild	Mild	Mild
Mongolia Gansu	Mild	Mild	Mild	Mild	Mild	Mild
Xinjiang	No	No	Mild	Mild	Mild	Mild
Shanxi	Extreme serious	Extreme serious	Extreme serious	Extreme serious	Extreme serious	Serious

Along with the trade of crops, a large amount of water resources in Northwest China were exported to all parts of the country in the form of virtual water, bringing severe water resource pressure on local area. It was observed that low crop yield and trade volume in Qinghai and Ningxia, local water resources can basically support crop production, so it was in a stress-free state. The water pressure in other provinces and autonomous region was higher than the national average. From 2000 to 2015, the Western Region of Inner Mongolia and Gansu have been in a state of mild stress, while Xinjiang was stress-free until 2006, but rose to a state of mild stress as local crop yield continued to climb. Due to the decrease in water footprint per unit area from 2012 to 2015, water resource pressure in Shaanxi decreased from extremely heavy pressure to severe pressure. However, Shaanxi still faced a very serious water resource pressure problem, and its water resource pressure was much higher than the national average water resource pressure. In general, the production and transportation of crops in Northwest China bring huge risk to local water security, and the sustainable use of water resources was restricted. However, with the continuous promotion of the 13th Five-Year Plan and the development strategy of Western China, the region will face greater water resources pressure in the future. A large amount of virtual water accompanied by the outflow of crops could make it impossible for the scarce water resources to continue to support local crop production in the future. In addition, the local ecological and environmental pressure was also far beyond its carrying capacity, which will inevitably affect the sustainable development of ecological environment and water resources and pose a threat to crop safety in China. Therefore, it is particularly important to adopt corresponding policies to alleviate local water resource pressure.

2.4 Economic effects associated with crop virtual water flow in Northwest China

By comparing the unilateral water economic benefits of the three major industries in Northwest China, as shown in Tab 3. It can be found that crop products with high water consumption and low income have relatively low economic benefits compared to industry and the third industry. For the northwest region, the economic benefits of the industrial water use and the third industry were about 30 to 40 times that of the agricultural water.

Together, the net output area of virtual water for crops, a large amount of water used for crop production due to the low value-added agricultural compared to other industries. The northwest region was equivalent to give up a higher opportunity cost to produce crop products. In the long run, there will be a big difference in the economic benefits between the virtual water input area and the output area. This will severely restrict the local economic development and urbanization process of industrialization, andalso intensify regional imbalance, that led to a vicious circle in which economic development will cautiously infantile and water-scarce areas will lagged behind and water and food security become more prominent.

Tab. 3 Economic benefits of three major industries in Northwest China in 2015

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Region	Agriculture	Industrial	Tertiary industry
Qinghai	10.15	308.23	333.60
Ningxia	4.07	222.66	344.90
Western Inner Mongolia	11.73	411.66	268.16
Gansu	10.35	153.28	293.11
Xinjiang	2.93	232.26	219.44
Shanxi	28.90	517.23	384.40

3 Conclusions and suggestions

In this study, water security and food security issues were viewed from the perspective of virtual water. Based on the theory of virtual water and water footprint, water resource pressure was taken as the foothold. it focused on the production and trade process of major crops in Northwest China from 2000 to 2015. From the perspective of water footprint and virtual water, it analyzed the virtual water flow accompanying agricultural products trade and the water resource pressure caused by sustainable utilization of local water resources, and achreved the following conclusions:

(1) There were different spatial and temporal trends in crop production and water footprint accompanying the process of crop production in the Northwest Provinces or Autonomous Regions of in China. Crop yield increased in Shaanxi and Gansu, but the water footprint decreased with the increase of crop yield. The crop yield and water footprint of Qinghai, first increased and then decreased. The

crop yield in Western Inner Mongolia showed an increasing trend, but with the increase of crop yield, the crop water footprint in Western Inner Mongolia increased from 2000 to 2009 and decreased from 2009 to 2015, due to the innovation of industrial and agricultural technology and equipment and the continuous progress of management mode. For the whole region, crop production in Northwest China increased, and the water footprint increased from 41.716 billion m^3 in 2000 to 43.987 billion m^3 in 2015 for regional crop production.

(2) The output of agricultural products trade in Northwest China was increasing every year, and the associated virtual flow momentum of agricultural products was also growing. It was assessed that the virtual flow momentum of regional crops increased from 21.981 billion m^3 (2000) to 27.299 billion m^3 (2015), with an increase of 24%. Meanwhile, the ratio of virtual water output in Northwest China increased every year, which was from 52.69 percent (2000) to 62.06 percent (2015).

(3) The virtual water flow associated the output of agricultural products will undoubtedly aggravate the contradiction of water resources in Northwest China. Inner Mongolia, Xinjiang and Gansu have higher water resource pressure than the national average level showed mild water resource pressure, while Shaanxi has severe water resource pressure. Northwest China will face a very serious water shortage in the future.

As an important grain-producing area in China, Northwest China has been exporting a large amount of water resources in the form of virtual water to all parts of the country in recent years with the trade of agricultural products, which further aggravated the contradiction between water supply and demand in this region. In order to ensure the future water security, food security and ecological security of the region, the integrated management of physical water and virtual water should be realized. Therefore, the following countermeasures and suggestions were proposed: (1) relying on science and technology to innovate the utilization efficiency of agricultural water resources, and to continue to increase high-yield breeding and water-saving agricultural technology research, and to improve the ability of dynamic monitoring and prediction of regional water resources. To promote efficient water-saving farmland construction through technical means and engineering measures to increase crop yield, and to reduce the loss of irrigation water for improving the level of farmland water use, and to realize efficient use of limited water resources. (2) to establish a virtual water compensation mechanism by relying on a management lever. In order to ensure the sustainable development of the social economy and ecosystem in Northwest China, it is suggested that to establish a virtual water compensation mechanism for agricultural products export from the national level. Within the framework of this mechanism, the virtual water input area submits a virtual water fee or virtual water compensation fee to the country each year through certain calculation rules, and the state returns a special fee to the virtual water output area in a certain way to implement water saving reconstruction, ecological restoration, water resources protection and other projects, therefore, to mobilize the enthusiasm of virtual water output area, promote the balanced sustainable development of regional economy. (3) relay on system optimization, and rational adjustment of regional industrial structure . At present, the establishment of a water-friendly industrial structure is an effective way to deal with the constraint of water resources in social and economical development. For the northwest water scarce areas, the matching conditions between the existing industrial structure and the local water resources carrying capacity should be further analyzed, and an industrial structure that is compatible with local resource conditions, location advantages, and economic development should be established to ensure the economic growth, ecological health and sustainable social development in the region.

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