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WANG Y，WANG H X，YANG Y X，et al. Review of quantitative research methods for Water-Energy-Food nexus[J]. South-to-North Water Transfers and Water Science & Technology，2020，18(6)：42-63. (in Chinese)

水-能源-粮食纽带关系定量研究方法综述

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摘要：在总结水-能源-粮食纽带关系研究中，使用频率较高或潜力较大的 8 种水-能源-粮食纽带关系定量研究方法为：水-能源-粮食纽带关系工具 2.0（WEF Nexus Tool 2.0）；生命周期评价（LCA）；可计算的一般均衡模型（CGE）；系统动力学模型（SD）；气候、土地、能源与水资源策略（CLEWS）；基于社会生态系统代谢的多尺度综合评价（MuSIASEM）；市场配置/市场配置系统集成模型（MARKAL/TIMES）和水资源评价规划模型-长期能源替代规划系统（WEAP-LEAP）。通过总结各研究方法的产生、发展及特性，并引用案例讨论其适用范围，分析其优缺点和在使用时需要注意的问题。在此基础上，对未来水-能源-粮食纽带关系定量研究方法的发展趋势进行讨论，认为伴随可持续发展问题关注度的上升与水-能源-粮食纽带关系内在机理的挖掘，未来的水-能源-粮食纽带关系定量研究方法将更加注重量化的精确性和数据的互通以及跨学科研究和多方法的耦合。本文可为水-能源-粮食纽带关系定量研究方法的选择和更新优化提供参考。

关键词：水-能源-粮食；纽带关系；定量研究；方法适用性；可持续发展

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2011 年 11 月，德国联邦政府在波恩召开的国际性会议上首次提出水-能源-粮食纽带关系（WEF nexus）的概念，纽带关系具体表现为：粮食的生产需要水和能源；水的提取和分配需要能源支持；能源的生产需要水；粮食的价格对化肥、灌溉、运输和加工等能源投入的成本也非常敏感。即水、能源和粮食三者之间存在复杂的关联联系，单一资源的稳定无法保障长期的社会稳定，需要在生产、消耗与管理过程中考虑这三者的耦合关系与潜在冲突，合理制定多资源战略。

随后，WEF nexus 受到了不同机构与组织的关注：联合国亚太经济与社会理事会（UNESCAP）[1]在 2013 年发布的《亚太地区水-粮食-能源纽带关系报告》提出了水-能源-粮食在时间和空间上具有紧密联系的特征；Pittock 等[2]研究了在集中生态环境与社会变化的影响下 WEF nexus 的动态变化与应对策略；亚洲开发银行（ADB）[3]从水资源管理的角度提出，针对 WEF nexus 的复杂性，需要提高水治理水平，改变粗放的水资源开发利用情况；联合国粮农组织（FAO）[4]在 2014 年分析了如何采用 WEF nexus 方法保障粮食安全和农业可持续发展。与此同时，WEF nexus 的定量研究取得了一定成就[5-6]，在研究方法上也有了一些革新与突破[7]。

国外对 WEF nexus 的研究方法进行了许多统计工作：国际可再生能源机构（International Renewable Energy Agency）[8]分别从输入数据、输出内容和分析特性等 3 个方面对 8 种不同的 WEF nexus 研究方法进行了总结；Semertzidis[9]从多种角度对联系能源系统和其他系统（如水、粮食和土地等）的建模方法进行分类，并讨论了不同的自上而下

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和自下而上研究方法的限制；Kaddoura 等[10]总结了 6 种用于制定综合性决策的 WEF nexus 建模方法的特性与优缺点，并指出目前 WEF nexus 建模方法的最大限制是对输入数据量的要求；Endo 等[11]归纳了 7 个研究区内水-粮食关系、水-能源关系、水-能源-粮食关系、水-能源-粮食-气候变化关系相关的 37 个项目中使用的研究方法；Dai 等[12]总结并归纳了 35 种水能关系的宏观建模方法，具体分为水-能源关系（WEN）方法、水-能源-环境关系（WEEN）方法、水-能源-粮食关系（WEFN）方法、水-能源-粮食-生态系统关系（WEFEN）方法和水-能源-土地利用-气候关系（WELCN）方法，并对每种建模方法进行了简要说明，其中 WEFN、WEFEN 和 WELCN 研究方法达 14 种；Zhang 等[13]讨论了 8 种 WEF nexus 建模方法的优缺点和适用范围，并指出没有任何一种方法适用于所有情形；Dargin 等[14]通过建立“复杂性指数”对 8 种 WEF nexus 研究方法的复杂性进行了评估，并指出，尽管复杂程度较高的方法能够更细致地捕捉纽带关系中的细节，但较为简单的方法在多系统整体的交互设计方面更胜一筹。

国内对于 WEF nexus 的研究方法缺乏归纳性成果，仅有李桂君等[15]对 WEF nexus 研究的数据和研究方法进行了简要的分类，并提出两两关系的量化已难以满足 WEF nexus 的研究需求。

目前，WEF nexus 研究已发展到理论与实践相结合的新阶段[15]。在定量研究成果不断涌现的同时，解决资源与发展问题的具体研究方法仍存在各自的局限[16]，鉴于此，对 WEF nexus 定量研究方法进行归纳与讨论是十分有必要的。通过对比发现，无论是选择的具体研究方法，还是在筛选过程中的侧重点，现有的 WEF nexus 定量研究方法综述之间均存在着较大的差别。这说明，WEF nexus 定量研究所选取的方法并不局限于特定的、重复的方法[16]，随着研究尺度、研究视角及研究时段等要素的改变，研究者可能会相应地依据学科偏好选择不同的研究方法。同时，新的研究方法正在生成，其他领域广泛应用的定量研究方法正在逐渐渗入 WEF nexus 研究领域，并被证明切实可行。考虑到 WEF nexus 定量研究方法的动态发展特征，本文选取 8 种在已有综述中高频出现的、或被证明在 WEF nexus 研究中存在较大潜力的定量研究方法，分别总结它们的原理、适用性和优缺点，并对其现阶段应用及未来发展趋势进行讨论，为 WEF nexus 定量研究方法的选择提供参考。

1　研究方法角度下的水-能源-粮食纽带关系的研究历程

WEF nexus 的研究历程可以分为以下两个阶段：定性研究阶段和定量研究阶段。定性研究阶段的主要工作是对 WEF nexus 内在机理的阐明，包括系统边界和系统间相互影响机制等。由于不同学者的研究尺度、研究目的和研究时段等因素不同[17]，WEF nexus 尚未达成统一定义，在不同的视角下对概念的理解[15]，形成了一种“百家齐鸣”的局面。该阶段从 2011 年开始发展到大约 2014 年。定量研究阶段的主要成果是运用 WEF nexus 的理念对实际问题做综合性解答。在 WEF nexus 的系统观在多领域被运用[18]的同时，其外延性逐渐被发掘，诸如 WEFEN（water-energy-food-ecosystem nexus）和 WELCN（water-energy-land use-climate change nexus）等衍生系统也成为较热门的研究对象[12]。同时，研究重心由双资源（水-能源、水-粮食、能源-粮食）的相互作用，逐渐过渡到多资源间的协调、平衡与可持续发展[16]。该阶段大约从 2014 年发展至今。

值得注意的是，两个阶段之间其实并没有明显的分界点，甚至可以说存在着一定的交叉部分：定性研究为定量研究提供理论基础，具体的案例应用又为 WEF nexus 概念的深化提供了实证依据与动力[19]。但总体上，人们对 WEF nexus 的研究呈现出了从定性研究到定量研究转变的趋势。

2　主要的水-能源-粮食纽带关系定量研究方法

在已有研究的基础上，本文选择了 8 种主要的 WEF nexus 定量研究方法，它们有些是从 WEF nexus 研究中发展出来的专门方法，有些是跨学科方法。具体的选择依据是：(1)能够从 WEF nexus 角度解决问题，能够量化和评估水、能源和粮食之间的联系，自身(或作为主要的研究方法)能够同时权衡 3 种资源对研究区域带来的影响。(2)考虑了 WEF nexus 的外延性，即环境、政策、经济和社会等外界因素的影响。(3)在 WEF nexus 研究领域有实际的应用案例，或在相互关系的研究中存在较大优势、经分析有应用于 WEF nexus 定量研究的潜力。(4)使用频率较高，并且在已有综述中被提及。

下面将分别从原理与特性、产生与发展、优势与不足，以及在 WEF nexus 研究中的适用性对选择的 8 种研究方法进行讨论。

2.1　水-能源-粮食纽带关系工具 2.0(WEF nexus Tool 2.0)

WEF nexus Tool 2.0 是基于情景分析的 WEF nexus 专门研究方法,基本原理是投入产出计算。通过输入研究区的粮食自给率、农业种植结构、供水结构、能源供给结构和粮食进出口数据设置情景模式,经由投入产出计算,得到水、能源和粮食之间的相互作用结果,如粮食生产对能源贸易的影响、水的处理与供应耗能和粮食生产所需虚拟水量等,同时,还计算了研究区的资金投入成本和二氧化碳排放量。最后,通过计算“可持续发展指数”对不同的情景模式进行评估。

最初,为了研究卡塔尔的可持续发展问题,Bassel 开发了 WEF nexus Tool 1.0,经卡塔尔环境与能源研究所完善构架后于 2013 年 10 月发布。在得到 20 多个国家以及 50 多个全球机构的试用反馈之后,WEF nexus Tool 1.0 的革新版本即 WEF nexus Tool 2.0 被推出。通过对卡塔尔的研究,Bassel 发现,水资源、能源和土地等因素对粮食供给方案的变化非常敏感,实现卡塔尔 WEF 可持续发展的重要途径是提高当地粮食产量,加大对适宜干旱地区生长的作物的研究,并重视农业贸易战略的调整[20]。该案例打破了传统的区域资源研究将水、能源和粮食作为独立系统分析的桎梏,识别了限制卡塔尔可持续发展的主要因素,为干旱国家和地区水-能源-粮食的协同优化提出了见解,也为全球 WEF nexus 的定量研究提供了方法与思路。

与大部分 WEF nexus 定量研究方法不同,WEF nexus Tool 2.0 在网页端即可操作,并提供无专业学科背景的人员也可以轻松使用的轻量化版本,有助于 WEF nexus 概念的传播普及。“可持续发展指数”由“资源指数”和“重要性系数”共同决定,既考虑了资源的客观限制,也遵从了决策者的主观偏好,增加了该方法在不同国家和地区的适用性。但 WEF nexus Tool 2.0 只能在静态时间点做评估[10],无法探寻在未来人口增长、气候改变等条件下 WEF nexus 的响应与发展,这是它的最大缺陷。另外,WEF nexus Tool 2.0 在对情景的简化过程中可能丢失了一些关键因素(如只从碳排放角度评估环境影响,忽略了废水排放和农业化肥施用带来的负面环境效益),难以满足精细模拟的需求。

2.2　生命周期评价(LCA)

LCA(life cycle assessment)是用于量化给定产品或工艺过程在其整个生命周期中对环境的影响的管理评价方法[13]。通过确定目标范围、清单分析、影响评估和改进分析 4 个步骤,记录研究对象在整个生命周期的输入、输出和潜在的环境影响,识别可能对环境产生重要影响的要素[21-22]。最早可追溯到 1969 年美国中西部研究所对可口可乐饮料包装瓶选材的研究,在之后的半个世纪,LCA 的方法体系与应用范围都有了极大的扩展。

环境与水资源、能源和粮食系统存在着紧密的联系,因此在 WEF nexus 研究中,采用 LCA 方法量化子系统对环境的影响,对实现水-能源-粮食的可持续发展十分重要。例如:Al-Ansari 等[23]提出了基于 WEF nexus 视角的改进 LCA 方法,将卡塔尔描述为农业子系统、水资源子系统和能源子系统的整合,对满足粮食自给自足前提下的多种技术配置情景进行了环境影响评估,发现家畜肠内发酵排放的温室气体对全球增温潜势(GWP)贡献最大,如果用太阳能来替代化石燃料,全球增温潜势将降低 30%;Jeswani 等[24]以 Kellogg Europe 公司生产的早餐麦片和谷物类零食为研究对象,通过 LCA 方法分析其生命周期的碳足迹、水足迹和能源足迹,探讨了完整的食品供应链对 WEF nexus 的影响,结果表明,即食谷物的原材料生产环节消耗了整个生命周期 90%的水,而制造环节对一次能源的消耗最大。在维持可持续发展与环境友好的大前提下,LCA 通过评价资源消耗过程中的环境影响,为 WEF nexus 的量化研究展示了一个新的切入点,以实现水资源、能源和粮食的可持续利用,从而减少对环境的负面效益,特别是对于不同子系统之间资源分配问题,提供了很好的决策思路与评价体系。

目前,LCA 的发展已经达到了比较高的水准,但仍存在着一定的限制:(1)高度依赖数据,难以应用于数据稀缺的地区[25]。(2)评价的时间成本和经济成本很高。(3)评价的重点放在对环境影响,对社会因素考虑欠缺[26]。(4)不适用于复杂系统的动态分析。(5)功能单元和系统边界的设置存在一定的主观性,导致计算中存在较大的截断误差[22]。

2.3　可计算的一般均衡模型(CGE)

CGE 模型(computable general equilibrium model)源于经济学家瓦尔拉斯的一般均衡理论,是一种被广泛应用于政策分析相关的宏观经济模型。典型的 CGE 模型就是用一组方程来描述供给、需求以及市场关系,在一系列优化条件的约束下,求解该方程组,得出各个市场都达到均衡时的一组数量和价格。

CGE 模型最突出的优势在于,可以通过价格机制评估政策变动对 WEF nexus 的影响,对于研究水

资源与资源环境、经济社会等复杂的关系有着重要的作用[27]，因此比较适用于 WEF nexus 的研究。Wianwiwat 等[28]通过 CGE 模型证明，虽然推广生物燃料的政策会在短期内提高农产品价格，并减少粮食的生产，但从长远看来，这种不利影响将逐渐得到控制。Ge 等[29]也做过相似的研究，证明了在不适宜种植粮食的地区发展生物燃料的生产，能够增加中国的粮食安全。在国内，何维达等[30]通过构建北京市水资源的 CGE 模型，模拟了北京市供水与用水政策对当地经济及水资源利用的影响，验证了南水北调工程对北京市经济发展的促进作用。CGE 模型在经济系统的各个组成部分之间建立起了数量联系，为宏观经济及其与自然资源系统的相互作用提供了全面的解释，对从经济学角度刻画 WEF nexus 起到了推动作用。

然而，CGE 模型存在着如下缺陷：(1)是定量分析模型，本身无法提供预测功能。(2)涉及大量参数，模型结果的有效性在很大程度上取决于模型校准中使用的数据质量。(3)模型中对于经济的假设较为简单，可能与实际情况不符，导致评估结果出现较大偏差。

2.4　系统动力学模型(SD)

SD 模型(system dynamics modelling)是一种基于因果机制的建模方法，由美国麻省理工学院福瑞斯特[31]在 1956 年创立。通过建立系统内变量之间的因果反馈回路，在宏观和微观层面上对多个系统进行全面的分析。它强调系统、整体的观点和联系、发展、运动的观点，结合定性与定量分析，易于解决经济、社会、生态环境等方面具有高阶次、非线性、复杂时变特点的系统问题。SD 模型相关软件有 DYNAMO、powersim、vensim、stella 和 ithink 等[32]。

作为可塑性较强的可视化仿真工具，SD 模型非常适合解决多学科问题[33]。在构建模型时考虑变量间的反馈与延迟，更符合真实的复杂系统，并可以同时对不同情景进行动态分析，为决策提供科学依据。通过 SD 建模来刻画 WEF nexus 的动态关联特征，有助于促进其实现从概念到实践的转变。目前国外已经有许多利用 SD 模型研究 WEF nexus 的成果：Halbe 等[34]以 Cyprus 为研究区，通过构建 WEF 反馈回路，讨论了从不同利益相关者的角度来实现该地区可持续发展的可能性；Hussien 等[18]基于对伊拉克 Duhok 市 419 户家庭的调查，采用自下而上的方法建立了家庭尺度的系统动力学模型，并考虑了家庭规模、饮食、收入以及气候对 WEF 终端使用的影响。国内的研究有：米红等[35]通过构建包含 17 个变量的系统动力学模型对我国的 WEF 系统进行了仿真；李桂君等[36]以北京市为研究区域，构建了以水-能源-粮食三者为主体并涵盖社会、经济和环境子系统的因果关联网络。这些研究成果表明，SD 模型适用于 WEF nexus 定量研究。

但是，SD 模型对真实系统的简化过程非常容易受到主观因素的影响，导致模型与现实不一致，需要通过不断地调试参数来增加模型的真实性。另外，对大量数据的需求也增加了 SD 模型构建的难度。

2.5　气候、土地、能源与水资源策略(CLEWS)

CLEWS(climate，land，energy and water strategies)是由 Howells 等[37]在 2013 年开发的以模块化的形式集合现有模拟工具的框架，通过识别系统间的反馈，分析它们之间的相互影响，以实现发展目标。它的工具包主要包括 WEAP(water evaluation and planning)、LEAP(long-range energy alternatives planning system)和 GAEZ(global agro-ecological zoning model)等[38]。

作为一个集成模型，CLEWS 兼具了复杂性和灵活性。一方面，它克服了单系统建模方法的固有限制，并且利用了系统思考的方法，更好地捕捉多个系统之间的复杂性；另一方面，对数据的要求降到了最低，便于在缺少可用数据的地区轻松应用[7]。CLEWS 通过研究水资源、能源、土地利用和外部压力(如气候变化)之间的相互作用，量化资源的利用、温室气体的排放和达到 WEF 安全目标所需要的成本，并支持政策协调和场景开发等功能，为 WEF nexus 的研究提供政策评估的帮助[12,38]。目前已应用于非洲、小岛屿发展中国家和欧洲跨界盆地的各种案例研究中，重点关注特定背景下的多资源关系问题，例如水资源可利用性、水力发电、生态系统强度和农业集约化之间的关系[14]。因此，CLEWS 对 WEF nexus 的研究有一定的协调辅助作用。

然而，CLEWS 也存在一定的缺陷，例如，在考虑了经济系统的同时并没有明确指出经济因素对实现未来发展目标的作用，导致经济系统框架的缺失[10]。CLEWS 模型的结构范围在未来有待于进一步扩展到与社会和经济模拟相结合的范围，例如人口、国内生产总值、城市化和国际贸易等，以实现完全集成的 WEF nexus 量化。

2.6　基于社会生态系统代谢的多尺度综合评价(MuSIASEM)

MuSIASEM(multi scale integrated analysis of societal and ecosystem metabolism)是由意大利学

者 Mario Giampietro 和日本学者 Kozo Mayumi[39] 在 20 世纪 90 年代提出的基于社会代谢理论的分析社会可持续发展状况的方法。它通过结合社会经济系统的“代谢”过程(如生物物理过程)与经济、人口、生态和社会特征,计算系统的人类活动时间、体外能投入量、劳动生产率、生物经济压力等数值,综合评估系统的发展水平与可持续性[40]。

MuSIASEM 最初用于分析现代社会能量代谢模式,现在已经扩展到 WEF nexus 的研究领域,分析探索水资源、能源和粮食的代谢模式与社会经济和生态变量之间的关系。Giampietro 等[41] 采用 MuSIASEM 方法对 3 个典型区域的 WEF 问题(毛里求斯共和国甘蔗生产生物燃料的选择分析、印度旁遮普省未来粮食生产的探索、南非共和国集中太阳能和木质生物质发电潜力的评估)进行了探究,并表示,将 MuSIASEM 方法应用于 WEF nexus 的过渡仍然存在一定的难度,主要体现在跨学科知识的理解与衔接、输入数据的预处理和将水、能源和粮食的实际消耗转化为“虚拟流”(如虚拟水)时产生的计算误差。但这 3 个案例,拓宽了 WEF nexus 研究的广度,不仅包含 WEF 系统本身,也考虑到了土地、经济、人力资本和生态系统,从社会经济和生态系统代谢的角度为 WEF nexus 的内部定量关系提供新的合理解释。

MuSIASEM 在不同尺度数据条件下的可用性都很高。在 WEF nexus 的研究中,MuSIASEM 可以通过使用复杂理论概念和生物经济学概念(flow-fund model)来同时描述与社会经济和生态变量相关联的 WEF“代谢”模式,并根据使用者的需要提供诊断和仿真的功能。然而,MuSIASEM 也存在着数据和结构方面的缺陷:(1)输入数据过于精细。(2)输出信息较多,难以解释和总结。(3)生物物理和经济流动之间的联系较难建立。(4)不能计算成本和收益,不能进行预测,无法提供不同发展模式的动态分析。

2.7　市场配置/市场配置系统集成模型(MARKAL/TIMES)

MARKAL(market allocation)是国际能源署(IEA)在 20 世纪 70 年代开发的综合型能源系统优化模型,可用于预测多地理尺度的能源-经济-环境演变。TIMES (the integrated MARKAL-EFOM system)是 MARKAL 的革新版。与 MARKAL 不同的是,TIMES 的仿真时间步长可以自定义,并且对能源使用时间的识别做了更灵活的细化。

MARKAL 和 TIMES 允许自定义能源使用时间,然后通过计算能源系统的最低成本路径,找到每个时间段的“最佳”参考能量系统,并能够分析与能源发展相关的技术投资和政策选择对水资源使用的影响[42]。因此在水能关系(WE)方面的研究成果比较突出,包括能源系统相关的技术投资和政策选择对用水的影响以及用水短缺情景下能源对水资源需求的变动[9]。尽管 MARKAL 和 TIMES 能够很好地捕捉能源系统的复杂性,但由于研究对象的限制,无法直接对水粮关系(WF)进行定量分析,且刻画多系统间关联的能力较弱,不能作为一个独立的 WEF nexus 研究方法来使用,因此常常与水资源/粮食/土地利用研究方法结合应用。另外,在国内 MARKAL 和 TIMES 多用于能源策略领域和气候变化领域[43-44],为 WEF nexus 的研究提供了可持续发展角度的新出口。

值得注意的是,MARKAL 和 TIMES 对输入数据的要求较高(尤其是在对历史数据校准时),且更适用于对未来情景的探索,不适合短期规划或应急响应。

2.8　水资源评价规划模型-长期能源替代规划系统(WEAP-LEAP)

WEAP 模型(water evaluation and planning)和 LEAP 模型(long-range energy alternatives planning system)是由斯德哥尔摩环境研究所(SEI)开发的两种软件模型,结构灵活,便于操作,在世界范围内被广泛应用。

WEAP 模型支持水资源综合评估,包括水资源供需比较及预测、不同管理模式对水质水量的影响。基于水收支平衡的原则,综合考虑用户端与供给端,通过概化水资源系统的要素,实现水资源系统的综合方法和政策导向问题的模拟,界面简洁,易于操作,并可以根据研究需要自行选择数据结构。LEAP 模型支持能源政策分析以及温室气体减排规划,支持自上而下和自下而上两种建模方式。输入数据分为能源需求模块、统计模块、转换模块、存储模块、资源模块以及无能源消费部门排放模块。结构较为灵活,使用者可以根据研究目的和数据可行性自行构建数据结构,并且综合考虑人口、技术、价格和经济发展等因素,可以模拟预测不同情景模式下的能耗和温室气体排放趋势。

尽管 WEAP 模型和 LEAP 模型各自能够对水资源及能源系统提供全面的刻画及分析,但多系统之间的关联联系却很薄弱,因此它们不能作为一个独立而完整的 WEF nexus 研究方法来使用。综合考虑两者的优势与缺陷,WEAP 模型和 LEAP 模型在 WEF nexus 的研究中通常被结合使用,例如

Karlberg 等[45]结合 WEAP 模型与 LEAP 模型，评估了埃塞俄比亚塔纳湖子流域的农业、能源和环境方面的不同发展模式的影响，分析了粮食-能源-环境系统中跨系统的联系与多资源的竞争关系。另外，WEAP 模型和 LEAP 模型也被用于 CLEW 的工具包中[46]。WEAP 和 LEAP 的结合使用为多模型耦合评价 WEF nexus 提供了很好的案例。

8 种 WEF nexus 研究方法的特点对比见表 1。

表 1　现阶段 8 种 WEF nexus 定量研究方法的特点对比

WEF nexus 研究方法	模型类型	适用尺度	适用研究视角	适用研究时间范围	是否适用动态分析	数据要求	补充
WEF Nexus Tool 2.0	仿真模型	国家尺度	无关	静态模拟	是	低	可以在线使用的情景分析模型
LCA	定量分析模型	国家尺度/流域尺度	无关	无关	否	高	环境评估方法
CGE	定量分析模型	国家尺度/全球尺度/区域尺度	自上而下	无关	否	高	经济模型
SD	仿真模型	多尺度	可选择，大部分自上而下	尤其适合中长期	是	高	多种软件选择，vensim 较常用
CLEWS	集成模型	多尺度	视工具包而定	中期	是	低	由不同子工具组成工具包
MuSIASEM	集成模型	国家尺度/区域尺度	无关	无关	否	高	—
MARKAL/TIMES	仿真模型	多尺度	自下而上	中长期	是	高	需要联合使用的能源模型
WEAP-LEAP	集成模型	国家尺度/区域尺度	自下而上	短期/长期	是	中等	需要联合使用的水资源/能源模型/单系统建模工具

3　对水-能源-粮食纽带关系定量研究方法的讨论

3.1　现阶段水-能源-粮食纽带关系定量研究方法的选择建议

3.1.1　从数据可行性出发筛选研究方法

不同的 WEF nexus 定量研究方法对数据的要求也不同。数据的广泛性和高分辨率通常被视为衡量研究方法复杂性的指标[14]。通常，复杂性较高的定量研究方法能够对 WEF 系统进行更全面、细致的分析，但研究范围也因此缩小了，例如，LCA 方法能够详细地评估资源在整个生命周期内的环境影响，对于联结 WEF 系统与环境系统具有很大的优势，但研究的重点也因此转移到了资源的环境影响，对于 3 种资源之间具体是怎样相互促进、相互制约的，以及它们的社会经济影响，并没有纳入考虑范围。一些复杂性较低的定量研究方法，例如 WEF Nexus Tool 2.0，对输入数据的要求较低，操作过程也较为简单，但相反地，输出结果却能够更好地捕获资源间的关联联系，以协同、整合的视角对研究区域的 WEF nexus 进行评估。因此，研究方法并不是越复杂越好，而是应综合考虑研究目标与数据可行性，筛选出既满足已有数据精度要求又适用于处理研究区主要问题的 WEF nexus 定量研究方法。

3.1.2　结合时空尺度的需求选择研究方法

水、能源和粮食作为 WEF nexus 的重要组成要素，会随着时间和空间呈动态变化，这在一定程度上增加了对 WEF nexus 定量研究方法的要求。一方面，研究对象的空间单元划分方式取决于输出端的精度需求，过于粗略的划分方式不利于结果的表达，而过于详密的划分方式增加了研究的投入成本，需结合研究区的 WEF nexus 具体特征与研究目标合理划分空间单元，在尽可能满足精度需求的前提下保持研究区 WEF nexus 特征的完整性。另一方面，时间尺度往往具有数据导向性，如果有模拟的需要，确定合适的模拟时间范围和步长，不仅会降低对数据的依赖性，也会减少运行与检验步骤的难度。

3.2　未来水-能源-粮食纽带关系定量研究方法的发展趋势

3.2.1　更加注重量化的精确性和数据的互通

目前，大部分 WEF nexus 的研究或多或少面临着对数据要求较高或数据缺乏的问题，这增加了前期数据收集和处理的难度，也是对研究方法提出的一项挑战。数据缺乏会导致结果区段性缺失，降低了可信度，而数据颗粒的大小又直接影响着结果的精确度。不同空间尺度的研究，对数据的要求也不尽相同。现阶段，WEF nexus 的定量研究通常选择

较小的或情况较为特殊、有显著研究意义的研究区[18,35,41]，但随着应用广度的延伸，WEF nexus 的概念可能会应用于更大的研究尺度。一般来说，系统的规模越大，越关注社会和经济数据[47]。然而，政府数据和其他已公布的数据由于统计口径和数据标准不同，数据质量参差不齐[48]，导致可用性受限，为 WEF nexus 的研究带来很大的不确定性。为解决上述问题，应努力提高 WEF nexus 研究的数据可用性：一方面，要在数据监测采集、数据处理和不确定性分析等方面下功夫；另一方面，通过标准化和模块化模型结构来使使用者在较低数据要求的输入条件下产生较为稳健的高精度结果。另外，水资源、能源和粮食三者之间的数据并不统一，这对决策造成了一定难度。因此，增加数据之间的互通性，也是 WEF nexus 定量研究方法的发展趋势之一。

3.2.2　更加注重跨学科研究和多方法耦合

由于 WEF nexus 是一个半开放系统，不仅存在着水资源系统、能源系统和粮食系统之间的相互作用，还会受到经济、社会、环境和土地等外部系统的扰动，同时，也影响着外部系统的稳定性。因此，在不同的学科背景下切换研究视角，能够丰富 WEF nexus 的内涵，提高应用强度与广度。关注近年来的研究成果，可以发现，随着 WEF nexus 概念的普及，研究对象的边界有着逐渐拓宽的趋势[12]。采用传统方法对水资源、能源和粮食进行封闭式的研究可能无法满足定量分析的需要，也在一定程度上失去了模拟预测的真实性。因此，在未来保守视角的专门 WEF nexus 定量研究方法的适用性可能会越来越低。

在进行定量分析或仿真时，WEF 系统中冗杂的要素可能会增加研究难度，并且对结果产生一定的干扰，难以析出重要结论。根据专业背景选取研究重点，从不同学科角度切入，化繁为简，凝炼有效信息，是未来 WEF nexus 定量研究的另一趋势。例如，CGE 本身是宏观经济模型，因其对经济系统刻画比较全面，很适合作为对资源环境与经济社会要素的输出有需求的 WEF nexus 研究。除了本文列举的 8 种定量研究方法之外，还存在着其他可用于 WEF nexus 定量研究的方法，如 Foreseer、PRIMA、iSDG Planning Model 等，但它们的关注重点大多放在对水-能源（WE）、水-粮食（WF）、能源-粮食（EF）等二元关系上，且现阶段适用性不及文中提到的 8 种研究方法，因此并未对其进行详细讨论。值得注意的是，无论是哪种 WEF nexus 定量研究方法，都不可避免地存在缺陷，没有任何一种研究方法能够适用于所有情形[11,49]。当下广泛使用的研究方法可能在以后受到各种各样的限制，目前未受关注的研究方法也很可能在以后 WEF nexus 的定量研究中大放异彩。因此，多模型耦合或者采取不同方法检验，能在一定程度上有效降低单一研究方法带来的结果疏漏或不确定性。

总的说来，目前 WEF nexus 领域的定量研究成果仍不足以全面解释全球可持续发展所面临的诸多资源性问题，就如同面对一幅偌大的拼图，仅仅站在相同的位置是难以将其拼凑完整的，在必要时切换角度，既能降低定量研究的工作难度，又能为审视 WEF nexus 提供全新的视野。

4　总结与展望

本文先后从方法特性、方法发展历史、方法优缺点以及在 WEF nexus 研究中的应用等方面对 8 种常见的 WEF nexus 定量研究方法进行了概述，通过对比能够发现，目前并没有任何一种研究方法是能完美应用于 WEF nexus 研究领域的。由于 WEF 系统是一个涉及人口、经济、社会、生态、气候和土地等外部因素的开放系统，内部与外部之间存在着不可忽略的物质与能量交换，单纯地将 WEF 系统与外部环境割裂开来独立研究是不可靠的，内部系统与外部环境的相互作用也应纳入研究范围，因此，能够联系多系统的 WEF nexus 研究方法可能适用性更广。并且，WEF nexus 具有明显的动态变化特征，支持动态分析的研究方法能够更好地捕捉 WEF 系统的变化，以及时提供决策与建议。另外，多研究尺度、研究视角和研究时段的切换，以及相对自由地定义情景模式，也是 WEF nexus 定量研究方法的趋势之一。

对于 WEF nexus 的研究，目前尚处于起步阶段，在选择研究方法时，应注意多方面对比综合，从数据可行性出发，结合研究的时空尺度需求，慎重选择定量研究方法。同时，也应注意量化的精确性和数据的互通程度，确保数据精度的统一和输出内容的兼容性，以方便数据再处理和结果的再应用。WEF nexus 的出口可能并不止于 WEF 系统，因此，降低与其他方法的对接难度，提高输出结果的泛用性，强调跨学科研究和多方法耦合，是未来 WEF nexus 定量研究方法的主要关注点。

参考文献：

[1]　ADNAN H. The status of the water, food and energy nexus in Asia and the Pacific[R]. Thailand: United Nations Economic and Social Commission for Asia and Pasific(UNESCAP), 2013: 13-18.

[2] PITTOCK J，HUSSEY K，MCGLENNON S. Australian climate，energy and water policies：conflicts and synergies[J]. Australian Geographer，2013，44(1)：3-22. DOI：10. 1080/00049182. 2013. 765345.

[3] DOMINGUEZ P. Thinking about water differently：managing the water-food-energy nexus[R]. Philippines：Asian Development Bank(ADB)，2013：25-26.

[4] FAO. The water-energy-food nexus：a new approach in support of food security and sustainable agriculture [EB/OL]. [2014-06]. http：//www. fao. org/policy-support/resources/resources-details/en/c/421718.

[5] SPIEGELBERG M，BALTAZAR D E，SARIGUMBA M P E，et al. Unfolding livelihood aspects of the water-energy-food nexus in the Dampalit Watershed，Philippines[J]. Journal of Hydrology：Regional Studies，2017 (11)：53-68. DOI：10. 1016/j. ejrh. 2015. 10. 009.

[6] 邓鹏，陈菁，陈丹，等. 区域水-能源-粮食耦合协调演化特征研究：以江苏省为例[J]. 水资源与水工程学报，2017(6)：232-238. DOI：10. 11705/j. issn. 1672-643X. 2017. 06. 41.

[7] BAZILIAN M，ROGNER H，HOWELLS M，et al. Considering the energy，water and food nexus：towards an integrated modelling approach[J]. Energy Policy，2011，39 (12)：7896-7906. DOI：10. 1016/j. enpol. 2011. 09. 039.

[8] FERROUKHI R，NAGPAL D，LOPEZ-PEÑA A，et al. Renewable energy and the water，energy and food nexus[R]. Abu Dhabi：International Renewable Energy Agency(IRENA)，2015：90-96.

[9] SEMERTZIDIS T. Can energy systems models address the resource nexus? [J]. Energy Procedia，2015(83)：279-288. DOI：10. 1016/j. egypro. 2015. 12. 182.

[10] KADDOURA S，EL KHATIB S. Review of water-energy-food nexus tools to improve the nexus modelling approach for integrated policy making[J]. Environmental Science and Policy，2017(77)：114-121. DOI：10. 1016/j. envsci. 2017. 07. 007.

[11] ENDO A，TSURITA I，BURNETT K，et al. A review of the current state of research on the water，energy，and food nexus[J]. Journal of Hydrology Regional Studies，2017(11)：20-30. DOI：10. 1016/j. ejrh. 2015. 11. 010.

[12] DAI J Y，WU S Q，HAN G Y，et al. Water-energy nexus：A review of methods and tools for macro-assessment[J]. Applied Energy，2018(210)：393-408. DOI：10. 1016/j. apenergy. 2017. 08. 243.

[13] ZHANG C，CHEN X X，LI Y，et al. Water-energy-food nexus：concepts，questions and methodologies [J]. Journal of Cleaner Production，2018(195)：625-639. DOI：10. 1016/j. jclepro. 2018. 05. 194.

[14] DARGIN J，DAHER B，MOHTAR R H. Complexity versus simplicity in water energy food nexus (WEF) assessment tools[J]. Science of the Total Environment，2019，650(1)：1566-1575. DOI：10. 1016/j. scitotenv. 2018. 09. 080.

[15] 李桂君，黄道涵，李玉龙. 水-能源-粮食关联关系：区域可持续发展研究的新视角[J]. 中央财经大学学报，2016 (12)：76-90. DOI：CNKI：SUN：ZYCY. 0. 2016-12-008.

[16] ALBRECHT T R，CROOTOF A，SCOTT C A. The water-energy-food nexus：A systematic review of methods for nexus assessment[J]. Environmental Research Letters，2018，13(4). DOI：10. 1088/1748-9326/aaa9c6.

[17] RINGLER C，BHADURI A，LAWFORD R. The nexus across water，energy，land and food (WELF)：potential for improved resource use efficiency? [J]. Current Opinion in Environmental Sustainability，2013，5(6)：617-624. DOI：10. 1016/j. cosust. 2013. 11. 002.

[18] HUSSIEN W A，MEMON F A，SAVIC D A. An integrated model to evaluate water-energy-food nexus at a household scale[J]. Environmental Modelling and Software，2017(93)：366-380. DOI：10. 1016/j. envsoft. 2017. 03. 034.

[19] LAWFORD R，BOGARDI J，MARX S，et al. Basin perspectives on the water-energy-food security nexus[J]. Current Opinion in Environmental Sustainability，2013，5 (6)：607-616. DOI：10. 1016/j. cosust. 2013. 11. 005.

[20] DAHER B T，MOHTAR R H. Water-energy-food (WEF) Nexus Tool 2. 0：guiding integrative resource planning and decision-making[J]. Water International，2015，40 (5-6)：1-24. DOI：10. 1080/02508060. 2015. 1074148.

[21] KEYS L K. Design for manufacture；design for the Life-Cycle；Systems Life-Cycle Engineering[C]// International Electronic Manufacturing Technology Symposium. USA：IEEE，1988：62-72. DOI：10. 1109/EMTS. 1988. 16151.

[22] NAIR S，GEORGE B，MALANO H M，et al. Water-energy-greenhouse gas nexus of urban water systems：review of concepts，state-of-art and methods[J]. Resources，Conservation and Recycling，2014(89)：1-10. DOI：10. 1016/j. resconrec. 2014. 05. 007.

[23] AL-ANSARI T，KORRE A，NIE Z，et al. Development of a life cycle assessment tool for the assessment of food production systems within the energy，water and food nexus[J]. Sustainable Production and Consumption，2015(2)：52-66. DOI：10. 1016/j. spc. 2015. 07. 005.

[24] JESWANI H，BURKINSHAW R，AZAPAGIC A. Environmental sustainability issues in the food-energy-water nexus：Breakfast cereals and snacks[J]. Sustainable Production and Consumption，2015(2)：17-28. DOI：10. 1016/j. spc. 2015. 08. 001.

[25] HAMICHE A M，STAMBOULI A B，FLAZI S. A review of the water-energy nexus[J]. Renewable and Sustainable Energy Reviews，2016(65)：319-331.

DOI:10.1016/j.rser.2016.07.020.
[26] BALKEMA A J,PREISIG H A,OTTERPOHL R,et al. Indicators for the sustainability assessment of wastewater treatment systems[J]. Urban Water,2002,4(2):153-161. DOI:10.1016/s1462-0758(02)00014-6.
[27] 王喜峰.水资源经济学的发展逻辑及进展[J].重庆理工大学学报(社会科学版),2017,31(1):37-44. DOI:10.3969/j.issn.1674-8425(s).2017.01.007.
[28] WIANWIWAT S,ASAFU-ADJAYE J. Is there a role for biofuels in promoting energy self sufficiency and security? A CGE analysis of biofuel policy in Thailand[J]. Energy Policy,2013(55):543-555. DOI:10.1016/j.enpol.2012.12.054.
[29] GE J P,LEI Y L,TOKUNAGA S. Non-grain fuel ethanol expansion and its effects on food security:a computable general equilibrium analysis for China[J]. Energy,2014,65(2):346-356. DOI:10.1016/j.energy.2013.10.093.
[30] 何维达,陆平,邓佩.北京市供水与用水政策的一般均衡分析:基于水资源 CGE 模型[J].河海大学学报(哲学社会科学版),2015,17(2):72-76. DOI:10.3876/j.issn.1671-4970.2015.02.014.
[31] FORRESTER J W. Industrial dynamics[J]. Journal of the Operational Research Society,1997,48(10):1037-1041. DOI:10.1057/palgrave.jors.2600946.
[32] 张波,虞朝晖,孙强,等.系统动力学简介及其相关软件综述[J].环境与可持续发展,2010,35(2):1-4. DOI:10.3969/j.issn.1673-288X.2010.02.001.
[33] NEWELL B,CRUMLEY C L,HASSAN N,et al. A conceptual template for integrative human-environment research[J]. Global Environmental Change,2005,15(4):299-307. DOI:10.1016/j.gloenvcha.2005.06.003.
[34] HALBE J,PAHLWOSTL C,LANGE M A,et al. Governance of transitions towards sustainable development-the water-energy-food nexus in Cyprus[J]. Water International,2015,40(5-6):1-18. DOI:10.1080/02508060.2015.1070328.
[35] 米红,周伟.未来 30 年我国粮食、淡水、能源需求的系统仿真[J].人口与经济,2010(1):1-7. DOI:CNKI:SUN:RKJJ.0.2010-01-001.
[36] 李桂君,李玉龙,贾晓菁,等.北京市水-能源-粮食可持续发展系统动力学模型构建与仿真[J].管理评论,2016,28(10):11-26. DOI:10.14120/j.cnki.cn11-5057/f.2016.10.002.
[37] HOWELLS M,HERMANN S,WELSCH M,et al. Integrated analysis of climate change,land-use,energy and water strategies[J]. Nature Climate Change,2013,3(7):621-626. DOI:10.1038/nclimate1789.
[38] SA′D S,DANIEL M,MICHELE V. Moving from theory to practice in the water-energy-food nexus:an evaluation of existing models and frameworks[J]. Water-Energy Nexus,2018,1(1):17-25. DOI:10.1016/j.wen.2018.04.001.
[39] GIAMPIETRO M,MAYUMI K. Multiple-scale integrated assessment of societal metabolism:introducing the approach[J]. Population and Environment,2000,22(2):109-153. DOI:10.1023/A:1026691623300.
[40] PASTORE G,GIAMPIETRO M,MAYUMI K. Societal metabolism and multiple-scale integrated assessment:empirical validation and examples of application[J]. Population and Environment,2000,22(2):211-254. DOI:10.1023/A:1026695724208.
[41] GIAMPIETRO M,ASPINALL R J,BUKKENS S G F,et al. An innovative accounting framework for the food-energy-water nexus: application of the MuSIASEM approach to three case studies[M]. Rome:Food and Agriculture Organisation of the United Nations,2013:56.
[42] CONNOLLY D,LUND H,MATHIESEN B V,et al. A review of computer tools for analysing the integration of renewable energy into various energy systems[J]. Applied Energy,2010,87(4):1059-1082. DOI:10.1016/j.apenergy.2009.09.026.
[43] 陈文颖,吴宗鑫.用 MARKAL 模型研究中国未来可持续能源发展战略[J].清华大学学报(自然科学版),2001,41(12):103-106. DOI:10.3321/j.issn:1000-0054.2001.12.033.
[44] 余岳峰,胡建一,章树荣,等.上海能源系统 MARKAL 模型与情景分析[J].上海交通大学学报,2008,42(3):360-364. DOI:10.3321/j.issn:1006-2467.2008.03.002.
[45] KARLBERG L,HOFF H,AMSALU T,et al. Tackling complexity:understanding the food-energy-environment nexus in Ethiopia's Lake Tana Sub-basin[J]. Water Alternatives,2015,8(1):710-734.
[46] WELSCH M,HERMANN S,HOWELLS M,et al. Adding value with CLEWS-Modelling the energy system and its interdependencies for Mauritius[J]. Applied Energy,2014(113):1434-1445. DOI:10.1016/j.apenergy.2013.08.083.
[47] PERRONE D,MURPHY J,HORNBERGER G M,et al. Gaining perspective on the water-energy nexus at the community scale[J]. Environmental Science & Technology,2011,45(10):4228-4234. DOI:10.1021/es103230n.
[48] ERNST K M,PRESTON B L. Adaptation opportunities and constraints in coupled systems:evidence from the U.S. energy-water nexus[J]. Environmental Science & Policy,2017(70):38-45. DOI:10.1016/j.envsci.2017.01.001.
[49] LIU J,YANG H,CUDENNEC C,et al. Challenges in operationalizing the water-energy-food nexus[J]. Hydrological Sciences Journal,2017,62(11):1714-1720. DOI:10.1080/02626667.2017.1353695.

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Review of quantitative research methods for Water-Energy-Food nexus

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Abstract: Eight quantitative WEF nexus (the water-energy-food nexus) research methods are frequently used or have great potential in the current research of WEF nexus. These methods include WEF Nexus Tool 2.0, Life Cycle Assessment (LCA), Computable General Equilibrium model (CGE), System Dynamics modeling (SD), Climate, Land, Energy and Water Strategies (CLEWS), Multi Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), Market Allocation/The Integrated MARKAL-EFOM System (MARKAL/TIMES) and Water Evaluation and Planning-Long-range Energy Alternatives Planning System (WEAP-LEAP). By summarizing the generation, development, and characteristics of 8 quantitative research methods, and citing cases to discuss their scope of application, the advantages and disadvantages of each research method and the key points that need to be paid attention for further use were analyzed. Besides, the trend of the development of quantitative research methods of WEF nexus in the future was also discussed. It is believed that with the increasing attention on sustainable development and the exploration of the internal mechanism of WEF nexus, the quantitative research methods of WEF nexus may need more attention to the accuracy of quantification and the interoperability of data, as well as the interdisciplinary research and multi-method coupling. This article can provide references for the selection and optimization of quantitative research methods of WEF nexus.

Key words: water-energy-food; nexus; quantitative research; method applicability; sustainable development

Introduction The concept of water-energy-food nexus (WEF nexus) was first introduced by the German Federal Government at an international conference in Bonn in November 2011. WEF nexus is reflected in the following aspects: food production requires water and energy; water extraction and distribution need to be supported energy; water is necessary for energy production; food price is very sensitive to the cost of energy input in chemical fertilizers, irrigation, transportation, and processing. In short, there is a complex nexus of water, energy, and food. The stability of a single resource does not guarantee long-term social security. Instead, it is necessary to consider their interaction and potential conflicts in production, consumption, and management, and formulate reasonable multi-resource strategies.

WEF nexus later received attention from various institutions and organizations. *The Report on the Water-Food-Energy Nexus in Asia Pacific Region* issued by the United Nations Economic and Social Commission for Asia and the Pacific (UNES-

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CAP)[1] in 2013 proposed that water, energy, and food are closely interlinked in time and space. Pittock et al. [2] studied the dynamic changes and coping strategies of WEF nexus under the influence of ecological and social changes. With respect to water resource management, Asian Development Bank (ADB)[3] suggested that the complexity of WEF nexus requires improving water management and changing the extensive exploitation of water resources. In 2014, the Food and Agriculture Organization(FAO) of the United Nations[4] analyzed how the WEF nexus approach can be used to guarantee food security and sustainable agricultural development. In the meantime, achievements have been made in the quantitative study of WEF nexus[5-6], with innovations and breakthroughs in research methodology[7].

The research methods of WEF nexus have been extensively reviewed in other countries. The International Renewable Energy Agency (IRENA)[8] summarized eight WEF nexus methods in terms of input data, output results, and analytical characteristics. Semertzidis[9] categorized the modeling approaches that link energy with other systems(e. g., water, food, and land) from multiple perspectives, and discussed the limitations of top-down and bottom-up research methods. Kaddoura et al. [10] outlined the characteristics as well as the advantages and disadvantages of six WEF nexus modeling methods used to make comprehensive decisions and pointed out that requirement for large amount of input data represents the major limitation of current WEF nexus modeling methods. Endo et al. [11] summarized the methods used in 37 projects associated with water-food, water-energy, water-energy-food, and water-energy-food-climate change relations in seven study areas. Dai et al. [12] reviewed the 35 macroscopic modeling approaches used for water-energy nexus, which were divided into water-energy nexus(WEN), water-energy-environment nexus (WEEN), water-energy-food nexus (WEFN), water-energy-food-ecosystem nexus (WEFEN), and water-energy-land use-climate nexus(WELCN). A brief description of each modeling method was provided, and 14 methods were devoted to WEFN, WEFEN, and WELCN. Zhang et al. [13] discussed the advantages/disadvantages and applicability of eight WEF nexus modeling methods, and pointed out that no method was suitable for all situations. Dargin et al. [14] assessed the complexity of eight WEF nexus methods by constructing a "complexity index", and suggested that although complex methods meticulously captured the details of nexus, simple methods were superior in the interaction design involving multiple systems.

The WEF nexus research methods used in China have not been reviewed. The only publication is a brief categorization of the data and methods of WEF nexus by Li et al. [15] who suggested that quantification of pairwise relationships was unsuitable for the study of WEF nexus.

Currently, the development of WEF nexus has entered a new stage in which theory and practice unite[15]. With the continuous emergence of quantitative research results, the specific research methods addressing resource and development problems still have their own limitations[16]. To address these issues, it is necessary to summarize and discuss the quantitative methods used in the study of WEF nexus to address these issues. Comparison reveals significant differences in existing quantitative WEF nexus research methods regarding the specific methods selected and the focus during selection, suggesting that the methods selected for the quantitative study of WEF nexus are not limited to specific and repeatedly used methods[16]. With the changes in research scale, perspective, and period, researchers may choose different methods according to disciplinary preferences. Meanwhile, new research methods are being developed, and the quantitative methods widely used in other fields are gradually introduced to WEF nexus and have proven to be practical. Given the dynamic development of WEF nexus quantitative research methods, we select eight quantitative methods that occur frequently in reviews or have been proven to have great potential in WEF nexus. We summarize their principles, applicability, advantages, and disadvantages, and discuss their current applications and future development, in order to provide a reference for the selection of quantitative methods in the study of WEF nexus.

1 History of study on WEF nexus from a methodology perspective

The history of WEF nexus study can be divided into two stages: qualitative research and quantitative research. The main task of qualitative research is to elucidate the mechanisms underlying WEF nexus, including system boundaries and intersystem interaction mechanisms. Due to different research scales, purposes, and periods[17], there is no generally accepted definition of WEF nexus, and understanding of the concept from different perspectives[15] has led to " a hundred schools of thought contend". This stage of development extends from 2011 to 2014. The main achievement of quantitative research is to offer comprehensive solutions to practical problems through the WEF nexus concept. With the systematic perspective of WEF nexus applied in multiple fields[18], its extension has been gradually explored, and the derived systems WEFEN and WELCN have become popular research objects[12]. At the same time the focus has gradually shifted from the interaction of two resources (water-energy, water-food, and energy-food) to the coordination, balance, and sustainable development of multiple resources[16]. This stage of development has occurred since 2014.

It is noteworthy that there is no clear cut-off point but an overlapping area between the two stages: qualitative research establishes the theoretical basis for quantitative research, whose application in specific cases provides the empirical basis and motivation for deepening the concept of WEF nexus[19]. In general, WEF nexus has developed from qualitative to quantitative studies.

2 Main quantitative methods for the study of WEF nexus

Based on existing literature, we select eight main quantitative research methods for WEF nexus, some are specifically developed for WEF nexus and others are interdisciplinary methods. The detailed selection criteria are described as follows. (1) The methods should have the ability to solve problems based on WEF nexus, to quantify and assess the interactions of water, energy, and food, and to weigh the impacts of the three resources on the study area independently (or as the primary research method). (2) The methods should consider the extensibility of WEF nexus, i. e., the influences of external factors such as environment, policy, economy, and society. (3) The methods should have practical cases in WEF nexus research, or great advantages in the study of interactions, or potential application to quantitative research of WEF nexus. (4) The methods should be frequently used and have been cited in existing reviews.

In the following sections, the eight selected research methods are discussed in terms of principles and characteristics, generation and development, advantages and disadvantages, and applicability in WEF nexus research.

2.1 WEF Nexus Tool 2.0

WEF Nexus Tool 2.0 is a special research method for WEF nexus based on scenario analysis and the principle of input-output calculation. The scenario is set by input of parameters of the study area, including food self-sufficiency, agricultural structure, water supply structure, energy supply structure, and food import/export data. Input-output calculation gives the interactions of water, energy, and food, such as the impact of food production on energy trade, energy consumption of water treatment and supply, and the virtual water volume required for food production. Next, the capital investment cost and CO_2 emissions of the study area are calculated. Finally, different scenarios are assessed through the calculation of the "sustainable development index".

To study the sustainable development in Qatar, Bassel first developed the WEF Nexus Tool 1.0, which was released in October 2013 after framework improvement by the Qatar Environment and Energy Research Institute. Based on the feedback from more than 20 countries and 50 organizations worldwide, an updated version, namely WEF Nexus Tool 2.0 was launched. Through the study of Qatar, Bassel found that water, energy, and land are highly sensitive to changes in food supply method, and that an important way to achieve sustainable development of WEF in Qatar is to increase local food production, support research on crops suitable for arid areas, and attach significance to the adjustment of agricultural trade strategies[20]. This case study breaks the limits of traditional research on regional resources in which water, energy, and food are analyzed as independent systems, and identifies the main factors limiting sustainable development in Qatar. These findings provide insights for synergistic optimization of water-energy-food in arid countries and regions, as well as methods and ideas for the quantitative study of WEF nexus worldwide.

Unlike most WEF nexus quantitative research methods, WEF Nexus Tool 2.0 can be operated via a web interface. It also provides a lightweight version that can be easily used by those without professional background, which helps spread and popularize the concept of WEF nexus. The "sustainable development index" is determined by "resource index" and "importance coefficient". The objective limitations of resources and the subjective preferences of decision makers are considered to increase the applicability of this method in different countries and regions. Nevertheless, WEF nexus Tool 2.0 can only be used in evaluation at static time points[10]. The major setback is the inability to explore the response and development of WEF nexus in the context of future population growth and climate change. In addition, WEF nexus Tool 2.0 may lose some key elements during scenario simplification (For instance, it assesses environmental impacts only from the perspective of carbon emissions, while neglecting the negative environmental benefits brought by wastewater discharge and chemical fertilizer application in agriculture), and thus it is unsuitable for detailed simulation.

2.2 Life cycle assessment (LCA)

LCA is a management evaluation method used to quantify the impact of a given product or process on the environment throughout its life cycle[13]. Through the four steps of goal and scope definition, inventory analysis, impact assessment, and interpretation, the inputs, outputs, and potential environmental influences throughout the life cycle of a study subject are recorded to identify the factors with possible significant impacts on environment[21-22]. LCA dates back to research on the selection of Coca-Cola bottle material by the Midwest Research Institute in the US in 1969. In the following half century, the methodology and application of LCA have been greatly expanded.

Environment is closely related to water, energy, and food systems. Therefore, it is critical to quantify the impacts of subsystems on environment with the LCA method, in order to achieve the sustainable development of water-energy-food in the study of WEF nexus. For example, Al-Ansari et al.[23] proposed an improved LCA method based on WEF nexus, which describes Qatar as the integration of agriculture, water resource, and energy subsystems. Environmental impact assessment was carried out in various technology allocation scenarios on the premise of food self-sufficiency, which found that the emitted greenhouse gases from fermentation in livestock intestine made the greatest contribution to the global warming potential (GWP), and GWP would be reduced by 30% if fossil fuels were replaced by solar energy. Jeswani et al.[24] studied breakfast cereals and cereal snacks produced by Kellogg Europe. The carbon, water, and energy footprints of their life cycles were analyzed by LCA to investigate the effect of a complete food supply chain on WEF nexus. The results showed that raw material production of ready-to-eat cereals consumed 90% of water used throughout the life cycle, while the manufacturing process consumed the largest proportion of primary energy[24]. On the premise of maintaining sustainable development and environmental friendliness, LCA shows a new entry point for quantitative study of WEF nexus by evaluating the environmental impact of resource consumption, in order to achieve sustainable use of water, energy, and food, and thereby to reduce negative environmental benefits. In particular, LCA provides a good decision-making strategy and evaluation system for the allocation of resources in subsystems.

LCA has currently been well developed but still has some limitations[22]: (1) high dependency on data and difficulty in application to areas with scarce data[25]. (2) high time and economic costs of evaluation. (3) focus on environmental impact without consideration of social factors[26]. (4) unsuitability for dynamic analysis of complex systems. (5) subjectivity in setting functional units and system boundaries and thus large truncation errors in calculation .

2.3 Computable general equilibrium (CGE) model

The CGE model was derived from the general equilibrium theory developed by economist Walras, and it is a macroeconomic model widely used in policy analysis. A typical CGE model uses a set of equations to describe the relationships of supply, demand, and market. Under various optimization constraints, this equation set is solved to obtain a group of quantity and price values when each market reaches equilibrium.

The most prominent advantage of CGE model is that the impact of policy change on WEF nexus is assessed through price mechanism. It has an important role in the study of the complex relationships of water resources with resource environment, economy, and society[27], and it is therefore more applicable to the study of WEF nexus. Wianwiwat et al. [28] demonstrated through CGE model that policies promoting biofuels would increase agricultural product price and reduce food production in the short term; however, this negative impact would be gradually brought under control in the long run. A similar study by Ge et al. [29] proved that biofuel production in areas unsuitable for growing food would raise food security in China. He et al. [30] constructed a CGE model of water resources in Beijing, China to simulate the impact of policies on water supply and use on local economy and water use, and verified that the South to North Water Transfer project played an important role in promoting the economic development of Beijing. The CGE model establishes quantitative relationships among the various components of economic system, provides a comprehensive explanation of macroeconomics and its interactions with natural resource systems, and thus promotes the depiction of WEF nexus from an economic point of view.

However, the CGE model suffers from the following shortcomings: (1) it is a quantitative model and cannot make predictions by itself. (2) many parameters are involved, and the validity of modeling results largely depends on the quality of data used in model calibration. (3) the simple economic assumptions used in the model may not truly reflect the actual situation, leading to large deviations in assessment results.

2.4 System dynamics (SD) model

The SD model is a modeling approach based on causal mechanism and was developed in 1956 by Professor Forrester at the Massachusetts Institute of Technology[31]. Through the establishment of a causal feedback loop among variables within a system, comprehensive analyses of multiple systems can be achieved at the macroscopic and microscopic levels. The SD model emphasizes a systematic and holistic point of view as well as the concepts of connection, development, and movement. It combines qualitative and quantitative analyses and is suitable for solving the system problems with high order, nonlinearity, and complex time-variation in the fields of economy, society, and ecological environment. The software programs used for the SD model include DYNAMO, powersim, vensim, stella, and ithink[32].

As a visual simulation tool with high plasticity, SD model is suitable for solving multidisciplinary problems[33]. Feedback and delay of variables are considered when building the model, which is more consistent with a real complex system. Dynamic analyses of different scenarios can be performed at the same time to provide a scientific basis for decision-making. Description of the dynamic network characteristics of WEF nexus by SD modeling facilitates the transformation from concept to practice. Many results in the study of WEF nexus with SD model have been reported in other countries. Halbe et al.[34] studied the possibility of achieving sustainable development in Cyprus from the perspective of different stakeholders by constructing a WEF feedback loop. Based on a survey of 419 households in Duhok City, Iraq, Hussien et al.[18] developed a household-scale SD model using a bottom-up approach involving the effects of family size, diet, income, and climate on WEF at end-use level. Mi et al.[35] simulated the WEF system in China by constructing a SD model with 17 variables. Li et al.[36] constructed a causal network of Beijing with water-energy-food as the main component, along with social, economic, and environmental subsystems. These findings suggest that the SD model is suitable for quantitative study of WEF nexus.

However, the simplification of real system by the SD model can be easily affected by subjective factors, leading to inconsistency between the model and reality that requires repeated parameter tuning to improve the authenticity of model. In addition, the need for large amounts of data also increases the difficulty of SD model construction.

2.5 Climate, land, energy, and water resource strategy (CLEWS)

CLEWS, which was developed by Howells et al.[37] in 2013, is a framework that can be used to integrate existing modular simulation tools. Through identification of the feedback of systems and analysis of how they interact with each other, the development goals can be achieved. CLEWS toolkits mainly include water evaluation and planning (WEAP), long-range energy alternatives planning system (LEAP), and global agro-ecological zoning model (GAEZ)[38].

As an integrated model, CLEWS is complex and flexible. On one hand, it overcomes the inherent limitations of single-system modeling approaches and uses systematic thinking to better capture the complexity of multiple systems. On the other hand, data requirement is minimized to facilitate application in areas with limited data available[7]. Through the research on the interactions of water resource, energy, land-use, and external pressures such as climate change, CLEWS quantifies the use of resources, the emission of greenhouse gases, and the costs required to meet the WEF security targets. CLEWS also supports policy coordination and scenario development to help evaluate policy in the study of WEF nexus[12,38]. CLEWS has been applied in various case studies in Africa, small island developing countries, and European transboundary basin, with a focus on multi-resource relationships in a given context, such as the relationships of water resource usability, hydropower, ecosystem intensity, and agricultural intensification[14]. Therefore, CLEWS coordinates and assists the study of WEF nexus.

However, CLEWS also has drawbacks. For example, the roles of economic factors on achieving future development goals are not clearly indicated in the consideration of economic systems, resulting in the lack of an economic framework[10]. The scope of the CLEWS model needs to be further expanded in the future to combine social and economic simulations, such as population, gross domestic product, urbanization, and international trade, in order to achieve fully integrated WEF nexus quantification.

2.6 Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM)

MuSIASEM, which was proposed in the 1990s by Italian scholar Mario Giampietro and Japanese scholar Kozo Mayumi[39], is an approach used to analyze the sustainability of social development based on social metabolism theory. Through the combination of the "metabolism" of socioeconomic systems (e.g., biophysical processes) with economic, demographic, ecological, and social characteristics, the values of human activity time, extracorporeal energy input, labor productivity, and bioeconomic stress of a system can be calculated to comprehensively assess the system's development level and sustainability[40].

Originally used to analyze the energy metabolism pattern in modern society, MuSIASEM has now been extended to the study of WEF nexus to analyze and explore the relationships of the metabolism patterns of water, energy, and food with socioeconomic and ecological variables. Using the MuSIASEM approach, Giampietro et al.[41] explored the WEF problems in three typical regions (analysis of options for biofuel production from sugarcane in the Republic of Mauritius, exploration of future food production in Punjab, India, and assessment of the power generation potential of concentrated solar and woody biomass in the Republic of South Africa). The authors showed that applying MuSIASEM to WEF nexus could be challenging, which is notably reflected in understanding and connecting interdisciplinary knowledge, pretreatment of input data, and calculation errors generated during the conversion of the actual consumption of water, energy, and food into "virtual flow" (such as virtual water). However, these three cases broaden the study of WEF nexus by encompassing not only the WEF system itself but also land, economy, human capital, and ecosystems, and thus provide new rational explanations for the quantitative relationships within WEF nexus from the perspective of social economy and ecosystem metabolism.

MuSIASEM is highly applicable at various data scales. In the study of WEF nexus, MuSIASEM describes the WEF "metabolism" patterns associated with socioeconomic and ecological variables using complex theoretical concepts and bioeconomic concepts (flow-fund model). It also allows users to perform diagnosis and simulation. However, MuSIASEM has some defects in data and structure: (1) requirement of detailed input data. (2) difficulty in explanation and summarization of the large volume of output information. (3) difficulty in establishing the links between biophysical processes and economic flow. (4) inability to calculate costs and benefits, to make predictions, and to provide the dynamic analysis of different development models.

2.7 Market allocation (MARKAL)/the integrated MARKAL-EFOM system (MARKAL/TIMES)

MARKAL is a comprehensive energy system optimization model developed by the International Energy Agency (IEA) in the 1970s and can be used to predict energy-economy-environment evolution on multiple geographic scales. TIMES is an updated version of MARKAL. Unlike MARKAL, TIMES allows customization of simulation time step and more flexible refinement of energy use time identification.

Energy use time can be customized in MARKAL and TIMES, the "best" reference energy system for each time period is then identified through calculation of the lowest cost path of the energy system, which is used for analyzing the impacts of technology investment and policy selection related to energy development on water resource use[42]. Therefore, remarkable results have been achieved in terms of water-energy (WE) relationship, including the impacts of technology investment and policy selection related to energy systems on water use, as well as on the changing demand for water resources by energy in water shortage scenarios[9]. Although MARKAL and TIMES well capture the complexity of energy systems, direct quantitative analysis of water-food (WF) relationship is limited by the subjects that can be assessed by these two methods. Moreover, the weakness in depicting the correlations of multiple systems prevents them from being used as independent WEF nexus research methods. Instead, they are often used in conjunction with water/food/land-use research methods. In addition, MARKAL and TIMES are mostly used in the fields of energy strategy and climate change in China[43-44], which provides a new direction of WEF nexus research from the perspective of sustainable development.

It is worth noting that MARKAL and TIMES have high requirements for input data (especially in the calibration of historical data) and are more suitable for exploring future scenarios but not for short-term planning or emergency response.

2.8 Water evaluation and planning-long range energy alternatives planning system (WEAP-LEAP)

WEAP and LEAP are two software models developed by Stockholm Environment Institute (SEI) and have been widely used worldwide because of their flexible structures and easy operations.

WEAP supports comprehensive assessment of water resources, including comparison and prediction of water supply and demand as well as the impacts of different management models on water quality and quantity. Based on the principle of water balance, water users and suppliers are considered comprehensively. The simulation of comprehensive methods and policy orientations of water resource system can be realized by generalizing elements in the system. WEAP has a user-friendly interface and easy operation, and allows the selection of data structure according to research needs. LEAP model supports energy policy analysis and greenhouse gas emission reduction planning, as well as top-down and bottom-up modeling methods. The input data are divided into the modules of energy demand, statistics, conversion, storage, resource, and emissions from non-energy-consuming sectors. Its flexible structure allows users to build their own data structures according to research objectives and data feasibility. It also gives comprehensive consideration of factors such as population, technology, price, and economic development in simulation and prediction of energy consumption and greenhouse gas emission trends in different scenarios.

Although WEAP model and LEAP model can each provide a comprehensive description and analysis of water resource and energy systems, the links between systems are weak. Therefore, they should not be used as independent and complete WEF nexus research methods. Considering their strengths and weaknesses, WEAP and LEAP are commonly used in combination in the study of WEF nexus. For example, Karlberg et al. [45] combined WEAP and LEAP to assess the impacts of different development patterns of agriculture, energy, and environment in Ethiopia's Lake Tana sub-basin, and to analyze the cross-system links and multi-resource competition in food-energy-environment system. In addition, WEAP and LEAP models are used in the CLEW toolkit[46]. The combination of WEAP and LEAP provides an excellent case study for combining multiple models in the evaluation of WEF nexus.

Comparison of the characteristics of the eight WEF nexus research methods is shown in Tab. 1.

Tab. 1 Comparison of the characteristics of eight WEF nexus quantitative research methods in the present stage

WEF nexus research methods	Models	Application scales	Application research perspectives	Application time frames	Dynamic analysis applicability	Data requirement	Others
WEF Nexus Tool 2.0	Simulation model	National scale	Irrelevant	Static simulation	Yes	Low	Scenario analysis models that can be used online
LCA	Quantitative analysis model	National/basin scales	Irrelevant	Irrelevant	No	High	Environmental assessment method
CGE	Quantitative analysis model	National/global/regional scales	Top-down	Irrelevant	No	High	Economic model
SD	Simulation model	Multiscale	Optional, mostly top-down	Especially suitable for medium/long terms	Yes	High	Various software available(vensim more commonly used)
CLEWS	Integrated model	Multiscale	Toolkit-dependent	Medium term	Yes	Low	Toolkit with different sub-tools
MuSIASEM	Integrated model	National/regional scales	Irrelevant	Irrelevant	No	High	—
MARKAL/TIMES	Simulation model	Multiscale	Bottom-up	Medium/long terms	Yes	High	Energy models used in combination
WEAP-LEAP	Integrated model	National/regional scales	Bottom-up	Short/long terms	Yes	Medium	Water/energy models used in combination/single system modeling tools

3　Discussion on quantitative research methods of WEF nexus

3.1　ecommendations for selection of quantitative research methods for WEF nexus in the present stage

3.1.1　Selection of research methods based on data feasibility

Different WEF nexus quantitative methods have different data requirements. Complex research methods often require data with high extensiveness and resolution[14]. Typically, complex quantitative methods can be used for more comprehensive and detailed analysis of WEF system, narrowing the scope of study. For example, LCA enables detailed assessment of the environmental impacts of resources throughout their life cycles, and has great advantage in linking WEF system with environmental system. However, the focus of research shifts to the environmental impacts of resources, rather than the specific promotion and limitation of the three resources and their socioeconomic influences. Less complex quantitative methods, such as WEF Nexus Tool 2.0, have low requirements for input data and simple operation processes. In contrast to complex methods, their outputs better capture the links of resources and evaluate WEF nexus in the study area from a synergistic, integrated view point. Therefore, complex methods do not necessarily lead to better results. What's more, research objectives and data feasibility should be considered comprehensively in the selection of WEF nexus quantitative research methods that not only match the accuracy of existing data but are also be suitable for addressing the main issues in the study area.

3.1.2　Selection of research methods based on spatial and temporal requirements

As important components of WEF nexus, water, energy, and food change dynamically with time and space, which to some extent increases the requirements for the quantitative methods used in the study of WEF nexus. On the one hand, the division of spatial unit of research objects depends on the requirement of output accuracy. Rough division is unfavorable for result expression, while fine division increases research input and cost. Therefore, it is necessary to reasonably divide the spatial unit in accordance with the specific characteristics and objectives of WEF nexus in the study area, in order to maintain the integrity of WEF nexus characteristics in the study area while the accuracy requirements are met. On the other hand, temporal scales tend to be data-oriented. If simulation is needed, appropriate simulation time and step size should be determined, in order to reduce the dependence on data and the difficulty of running and verifying the simulation.

3.2　Future development in quantitative research methods of WEF nexus

3.2.1　Focus on quantitative accuracy and data interoperability

Currently, most WEF nexus studies are confronted with various levels of problems derived from high requirements and low availability of data, which increases the difficulty of data collection and processing in the early stage, and poses a challenge to the research methods. Lack of data results in missing parts and reduced credibility of results, while the size of data points directly affects the accuracy of results. Studies on different spatial scales have different requirements for data. Current quantitative studies of WEF nexus usually select small or special study areas with great research significance[18,35,41]. However, with the extension of application, the concept of WEF nexus may be applied to larger research scales. In general, larger systems place greater attention on social and economic data[47]. However, the quality of data published by government and other agencies varies due to differences in statistical specifications and data standards[48]. This leads to limited usability and great uncertainty to the study of WEF nexus. Data usability should be improved in WEF nexus studies to solve this problem. On the one hand, efforts should be made in data monitoring, collection, processing, and uncertainty analysis. On the other hand, standardized and modular model structures should be used to allow users to produce robust, high-accuracy results with low input data requirements. In addition, the heterogeneity of data on water, energy, and food causes some difficulty in decision-making. Therefore, increasing the interoperability of data is also a direction for the development of WEF nexus quantitative research methods.

3.2.2 Emphasis on interdisciplinary research and multi-method interaction

Since WEF nexus is a semi-open system, there are not only interactions of water, energy, and food systems but also perturbations from external systems such as economic, society, environment, and land. Meanwhile, the stability of external systems is influenced by WEF nexus. Therefore, changing research perspectives in different subject contexts can enrich the connotation of WEF nexus and improve its intensity and extent of application. Studies in recent years suggest that the boundary of study subjects has been gradually extended with the popularization of WEF nexus concept[12]. The closed study of water, energy, and food with traditional methods may be unsuitable for quantitative analysis and lose some authenticity in simulation and prediction. Hence, the applicability of conservative and specialized quantitative research methods in WEF nexus may continuously decrease in the future.

In quantitative analysis or simulation, the redundant elements in WEF system may increase the difficulty of research and interfere with the results, making it difficult to draw important conclusions. Selection of research focus according to professional background, entry from different disciplinary perspectives, simplification of complex systems, and condensation of valid information represent another trend of future quantitative research on WEF nexus. For example, the CGE is a macroeconomic model for comprehensive depiction of economic systems, and it is suitable for WEF nexus with a demand for output of resource environment as well as economic and social factors. In addition to the eight quantitative research methods listed in this paper, there are other methods that can be used for the quantification of WEF nexus, such as Foreseer, PRIMA, and iSDG Planning Model. However, they focus on binary relationships such as water-energy (WE), water-food (WF), and energy-food (EF), and are less applicable in the present stage as compared with the above eight methods, so they were not discussed in detail. Notably, all WEF nexus quantitative research methods have shortcomings, and no method can be applicable to all situations [11,49]. The research methods that are widely used today may be subject to various restrictions tomorrow. The research methods currently out of focus may shed light on the quantitative study of WEF nexus in the future. Therefore, interactions of multiple models or verification with different methods can effectively reduce the omission or uncertainty of results caused by just a single method.

In conclusion, current findings in the quantitative study of WEF nexus fall short in fully explaining the resource issues facing the global sustainable development, which is like a large jigsaw puzzle, and it is difficult to piece it together just standing in the same position. Changing standpoint when necessary reduces the difficulty of quantitative research and provides a fresh perspective for studying WEF nexus.

4 Summary and outlook

In this paper, we summarize eight common quantitative research methods for WEF nexus in terms of characteristics, development history, advantages and disadvantages, and applications in WEF nexus. By comparison, we find that there is no single research method that is perfectly applicable to WEF nexus research. Since WEF is an open system involving external factors such as population, economy, society, ecology, climate, and land, there are non-negligible exchanges of matter and energy between the interior and the exterior. Therefore, the study would be unreliable if WEF were simply isolated from the external environment, and the interactions between the internal system and the external environment should be included in the study. Thus, the WEF nexus research methods that link multiple systems may have broader applications. Moreover, WEF nexus changes dynamically, and the research methods that support dynamic analysis can better capture the changes in WEF system and provide decisions and suggestions in a timely manner. In addition, the use of different study scales, perspectives, and periods as well as the relatively free definition of scenarios represent a trend in the development of WEF nexus quantitative research methods.

The study of WEF nexus is still in its infancy. The quantitative research methods should be carefully selected by paying attention to the comparison and synthesis of multiple aspects, starting from data feasibility, and combining the spatial and temporal scales of research. In the meantime, attention should also be paid to quantification accuracy and data interoperability to ensure the uniformity of data accuracy and the compatibility of output to facilitate data reprocessing and result reuse. The research on WEF nexus may go beyond the WEF system. Therefore, reducing the difficulty of integration with other methods, improving the generality of output, emphasizing interdisciplinary research, and combining multiple methods are the main concerns of WEF nexus quantitative research methods in the future.

References:

[1] ADNAN H. The status of the water, food and energy nexus in Asia and the Pacific[R]. Thailand: United Nations Economic and Social Commission for Asia and Pasific(UNESCAP), 2013: 13-18.

[2] PITTOCK J, HUSSEY K, MCGLENNON S. Australian climate, energy and water policies: conflicts and synergies[J]. Australian Geographer, 2013, 44(1): 3-22. DOI: 10.1080/00049182.2013.765345.

[3] DOMINGUEZ P. Thinking about water differently: managing the water-food-energy nexus[R]. Philippines: Asian Development Bank(ADB), 2013: 25-26.

[4] FAO. The water-energy-food nexus: a new approach in support of food security and sustainable agriculture [EB/OL]. [2014-06]. http://www.fao.org/policy-support/resources/resources-details/en/c/421718.

[5] SPIEGELBERG M, BALTAZAR D E, SARIGUMBA M P E, et al. Unfolding livelihood aspects of the water-energy-food nexus in the Dampalit Watershed, Philippines[J]. Journal of Hydrology: Regional Studies, 2017 (11): 53-68. DOI: 10.1016/j.ejrh.2015.10.009.

[6] DENG P, CHEN J, CHEN D, et al. The evolutionary characteristics analysis of the coupling and coordination among water, energy and food: Take Jiangsu Province as an example[J]. Journal of Water Resources & Water Engineering, 2017(6): 232-238. (in Chinese) DOI: 10.11705/j.issn.1672-643X.2017.06.41.

[7] BAZILIAN M, ROGNER H, HOWELLS M, et al. Considering the energy, water and food nexus: towards an integrated modelling approach[J]. Energy Policy, 2011, 39(12): 7896-7906. DOI: 10.1016/j.enpol.2011.09.039.

[8] FERROUKHI R, NAGPAL D, LOPEZ-PEÑA A, et al. Renewable energy and the water, energy and food nexus[R]. Abu Dhabi: International Renewable Energy Agency(IRENA), 2015: 90-96.

[9] SEMERTZIDIS T. Can energy systems models address the resource nexus? [J]. Energy Procedia, 2015(83): 279-288. DOI: 10.1016/j.egypro.2015.12.182.

[10] KADDOURA S, EL KHATIB S. Review of water-energy-food nexus tools to improve the nexus modelling approach for integrated policy making[J]. Environmental Science and Policy, 2017(77): 114-121. DOI: 10.1016/j.envsci.2017.07.007.

[11] ENDO A, TSURITA I, BURNETT K, et al. A review of the current state of research on the water, energy, and food nexus[J]. Journal of Hydrology Regional Studies, 2017(11): 20-30. DOI: 10.1016/j.ejrh.2015.11.010.

[12] DAI J Y, WU S Q, HAN G Y, et al. Water-energy nexus: A review of methods and tools for macro-assessment[J]. Applied Energy, 2018(210): 393-408. DOI: 10.1016/j.apenergy.2017.08.243.

[13] ZHANG C, CHEN X X, LI Y, et al. Water-energy-food nexus: concepts, questions and methodologies [J]. Journal of Cleaner Production, 2018(195): 625-639. DOI: 10.1016/j.jclepro.2018.05.194.

[14] DARGIN J, DAHER B, MOHTAR R H. Complexity versus simplicity in water energy food nexus (WEF) assessment tools[J]. Science of the Total Environment, 2019, 650(1): 1566-1575. DOI: 10.1016/j.scitotenv.2018.09.080.

[15] LI G J, HUANG D H, LI Y L. Water-energy-food nexus (WEF-Nexus): new perspective on regional sustainable development[J]. Jour of University of Finance & Economics, 2016(12): 76-90. (in Chinese)

OI:CNKI:SUN:ZYCY. 0. 2016-12-008.

[16] ALBRECHT T R, CROOTOF A, SCOTT C A. The water-energy-food nexus: a systematic review of methods for nexus assessment[J]. Environmental Research Letters, 2018, 13(4). DOI: 10. 1088/1748-9326/aaa9c6.

[17] RINGLER C, BHADURI A, LAWFORD R. The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? [J]. Current Opinion in Environmental Sustainability, 2013, 5(6): 617-624. DOI: 10. 1016/j. cosust. 2013. 11. 002.

[18] HUSSIEN W A, MEMON F A, SAVIC D A. An integrated model to evaluate water-energy-food nexus at a household scale[J]. Environmental Modelling and Software, 2017(93): 366-380. DOI: 10. 1016/j. envsoft. 2017. 03. 034.

[19] LAWFORD R, BOGARDI J, MARX S, et al. Basin perspectives on the water-energy-food security nexus [J]. Current Opinion in Environmental Sustainability, 2013, 5(6): 607-616. DOI: 10. 1016/j. cosust. 2013. 11. 005.

[20] DAHER B T, MOHTAR R H. Water-energy-food (WEF) Nexus Tool 2. 0: guiding integrative resource planning and decision-making[J]. Water International, 2015, 40(5-6): 1-24. DOI: 10. 1080/02508060. 2015. 1074148.

[21] KEYS L K. Design for manufacture; design for the Life-Cycle; Systems Life-Cycle Engineering[C]// International Electronic Manufacturing Technology Symposium. USA: IEEE, 1988: 62-72. DOI: 10. 1109/ EMTS. 1988. 16151.

[22] NAIR S, GEORGE B, MALANO H M, et al. Water-energy-greenhouse gas nexus of urban water systems: review of concepts, state-of-art and methods[J]. Resources, Conservation and Recycling, 2014(89): 1-10. DOI: 10. 1016/j. resconrec. 2014. 05. 007.

[23] AL-ANSARI T, KORRE A, NIE Z, et al. Development of a life cycle assessment tool for the assessment of food production systems within the energy, water and food nexus[J]. Sustainable Production and Consumption, 2015(2): 52-66. DOI: 10. 1016/j. spc. 2015. 07. 005.

[24] JESWANI H, BURKINSHAW R, AZAPAGIC A. Environmental sustainability issues in the food-energy-water nexus: Breakfast cereals and snacks[J]. Sustainable Production and Consumption, 2015(2): 17-28. DOI: 10. 1016/j. spc. 2015. 08. 001.

[25] HAMICHE A M, STAMBOULI A B, FLAZI S. A review of the water-energy nexus[J]. Renewable and Sustainable Energy Reviews, 2016(65): 319-331. DOI: 10. 1016/j. rser. 2016. 07. 020.

[26] BALKEMA A J, PREISIG H A, OTTERPOHL R, et al. Indicators for the sustainability assessment of wastewater treatment systems[J]. Urban Water, 2002, 4(2): 153-161. DOI: 10. 1016/s1462-0758(2) 00014-6.

[27] WANG X F. Research on the historic logic and development of water resources economics[J]. Journal of Chongqing Institute of Technology, 2017, 31(1): 37-44. (in Chinese) OI: 10. 3969/j. issn. 1674-8425 (s). 2017. 01. 007.

[28] WIANWIWAT S, ASAFU-ADJAYE J. Is there a role for biofuels in promoting energy self sufficiency and security? A CGE analysis of biofuel policy in Thailand [J]. Energy Policy, 2013(55): 543-555. DOI: 10. 1016/j. enpol. 2012. 12. 054.

[29] GE J P, LEI Y L, TOKUNAGA S. Non-grain fuel ethanol expansion and its effects on food security: a computable general equilibrium analysis for China[J]. Energy, 2014, 65(2): 346-356. DOI: 10. 1016/j. energy. 2013. 10. 093.

[30] HE W D, LU P, DENG P. General equilibrium analysis of Beijing's water supply and consumption policies based on CGE-Water model[J]. Journal of Hohai University (Philosophy and Social Sciences), 2015, 17 (2): 72-76. (in Chinese) OI: 10. 3876/j. issn. 1671-4970. 2015. 02. 014.

[31] FORRESTER J W. Industrial dynamics[J]. Journal of the Operational Research Society, 1997, 48(10): 1037-1041. DOI: 10. 1057/palgrave. jors. 2600946.

[32] ZHANG B, YU Z H, SUN Q, et al. The introduction to system dynamics and relating software[J]. Environment and Sustainable Development, 2010, 35(2): 1-4. (in Chinese) OI: 10. 3969/j. issn. 1673-288X. 2010. 02. 001.

[33] NEWELL B, CRUMLEY C L, HASSAN N, et al. A conceptual template for integrative human-environment research[J]. Global Environmental Change, 2005, 15(4): 299-307. DOI: 10. 1016/j. gloenvcha. 2005. 06. 003.

[34] HALBE J, PAHLWOSTL C, LANGE M A, et al. Governance of transitions towards sustainable development-the water-energy-food nexus in Cyprus[J]. Water International, 2015, 40(5-6): 1-18. DOI: 10. 1080/02508060. 2015. 1070328.

[35] MI H, ZHOU W. The system simulation of China's grain, fresh water and energy demand in the next 30

years[J]. Population and Economics,2010(1):1-7.(in Chinese) OI:CNKI:SUN:RKJJ.0.2010-01-001.

[36] LI G J,LI Y L,JIA X J,et al. Establishment and simulation study of system dynamic model on sustainable development of water-energy-food nexus in Beijing [J]. Management Review,2016,28(10):11-26.(in Chinese) DOI:10.14120/j.cnki.cn11-5057/f.2016.10.002.

[37] HOWELLS M,HERMANN S,WELSCH M,et al. Integrated analysis of climate change,land-use,energy and water strategies[J]. Nature Climate Change,2013,3(7):621-626. DOI:10.1038/nclimate1789.

[38] SA'D S,DANIEL M,MICHELE V. Moving from theory to practice in the water-energy-food nexus:an evaluation of existing models and frameworks[J]. Water-Energy Nexus,2018,1(1):17-25. DOI:10.1016/j.wen.2018.04.001.

[39] GIAMPIETRO M,MAYUMI K. Multiple-scale integrated assessment of societal metabolism:introducing the approach[J]. Population and Environment,2000,22(2):109-153. DOI:10.1023/A:1026691623300.

[40] PASTORE G,GIAMPIETRO M,MAYUMI K. Societal metabolism and multiple-scale integrated assessment:empirical validation and examples of application [J]. Population and Environment,2000,22(2):211-254. DOI:10.1023/A:1026695724208.

[41] GIAMPIETRO M,ASPINALL R J,BUKKENS S G F,et al. An innovative accounting framework for the food-energy-water nexus: application of the MuSIASEM approach to three case studies[M]. Rome: Food and Agriculture Organisation of the United Nations,2013:56.

[42] CONNOLLY D,LUND H,MATHIESEN B V,et al. A review of computer tools for analysing the integration of renewable energy into various energy systems [J]. Applied Energy,2010,87(4):1059-1082. DOI:10.1016/j.apenergy.2009.09.026.

[43] CHEN W Y,WU Z X. Study on China's future sustainable energy development strategy using MARKAL model[J]. Journal of Tsinghua University (Science and Technology),2001,41(12):103-106.(in Chinese) DOI:10.3321/j.issn:1000-0054.2001.12.033.

[44] YU Y F,HU J Y,ZHANG S R,et al. Study on Shanghai energy system MARKAL model and scenario analysis[J]. Journal of Shanghai Jiaotong University,2008,42(3):360-364.(in Chinese) DOI:10.3321/j.issn:1006-2467.2008.03.002.

[45] KARLBERG L,HOFF H,AMSALU T,et al. Tackling complexity: understanding the food-energy-environment nexus in Ethiopia's Lake Tana Sub-basin [J]. Water Alternatives,2015,8(1):710-734.

[46] WELSCH M,HERMANN S,HOWELLS M,et al. Adding value with CLEWS-Modelling the energy system and its interdependencies for Mauritius[J]. Applied Energy,2014(113):1434-1445. DOI:10.1016/j.apenergy.2013.08.083.

[47] PERRONE D,MURPHY J,HORNBERGER G M,et al. Gaining perspective on the water-energy nexus at the community scale[J]. Environmental Science & Technology,2011,45(10):4228-4234. DOI:10.1021/es103230n.

[48] ERNST K M,PRESTON B L. Adaptation opportunities and constraints in coupled systems:evidence from the U.S. energy-water nexus[J]. Environmental Science & Policy,2017(70):38-45. DOI:10.1016/j.envsci.2017.01.001.

[49] LIU J,YANG H,CUDENNEC C,et al. Challenges in operationalizing the water-energy-food nexus [J]. Hydrological Sciences Journal,2017,62(11):1714-1720. DOI:10.1080/02626667.2017.1353695.