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Big Earth Data Supports Synergies and Trade-offs of Sustainable Development Goals: Progress and Prospect

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Big Earth Data Supports Synergies and Trade-offs of Sustainable Development Goals: Progress and Prospect

Abstract

The United Nations Sustainable Development Goals (SDGs) are an important guide for different countries and regions to achieve sustainable economic, social, and environmental developments. They include 17 goals and 169 specific targets. The interactions among the goals can be manifested as synergy or trade-off; that is, implementing one or more goals may positively or negatively affect other goals. At present, important progress has been made in the monitoring and evaluation of individual goals. However, our understanding of the synergies and trade-offs among multiple SDGs is still limited. Firstly, this paper describes the current progress in the synergy and trade-offs of SDGs from three aspects: comprehensive analyses of all the SDGs, thematic analyses of few relevant SDGs, and the relationship of the specific indicators under certain SDG. Secondly, in view of the data bottleneck in the current studies, combined with the latest progress of the Big Earth Data, this paper showcases the typical scenarios of the Big Earth Data supporting studies of the synergy and trade-off of SDGs. Thirdly, the Big Earth Data's potential and future research prospects on the synergies and trade-offs of SDGs are proposed. This study shows that SDG synergy and trade-off analyses have experienced three stages: a semiquantitative evaluation based on expert knowledge, correlation analyses based on statistical data, and quantitative analyses based on the Big Earth Data. Different data sources from different countries could lead to varying results, and the Big Earth Data plays a vital role in promoting data consistency and transparency between countries. Therefore, it provides crucial support for the understanding of synergies and trade-offs of SDGs. The purpose of this study is to summarize the latest progress of synergy and trade-off studies of SDGs, which has received less attention in SDG-related research, and to support decision making for realizing the economic, environmental, and social goals together.

Keywords

Big Earth Data, sustainable development goals (SDGs), synergy

Authors

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地球大数据支撑可持续发展目标 协同与权衡研究：进展与展望

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摘要 联合国《改变我们的世界：2030年可持续发展议程》是各国实现经济、社会和环境共同发展的重要指南。当前，该议程的17个可持续发展目标（SDGs）的监测和评价已取得重要进展，但各SDGs间相互作用，特别是SDGs间的协同和权衡关系的认知仍较有限。文章首先从全部目标关系的综合分析、典型多目标关系分析、单目标内子指标间的关系3个方面描述了当前SDGs协同与权衡的研究进展和主要发现；并针对研究中的数据瓶颈问题，剖析了地球大数据支撑多目标协同和权衡的思路及典型案例；在此基础上，对地球大数据促进SDGs协同和权衡研究进行了展望。研究表明，地球大数据在提升SDG指标数据一致性、透明性、时效性和准确性等方面能够发挥重要作用，可以改进前期基于专家知识或统计数据等方法的不足，为提升多目标协同和权衡研究的定量水平提供重要数据支撑。最后，应对SDGs权衡的挑战，提出了完善地球大数据支撑SDGs协同与权衡的方法体系并构建模拟与预警平台、加强不同领域和主体的合作、强化技术创新推动等建议。

关键词 地球大数据，可持续发展目标，权衡，协同

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联合国《改变我们的世界：2030年可持续发展议程》（以下简称《2030年可持续发展议程》）旨在评价和解决目前面临的经济、社会和环境等多个方面的

复杂挑战；与之前关注的有限维度的发展议程相比，其提供了一个全面和多维的发展观，包括17项可持续发展目标（SDGs）和169项具体目标。各目标相互作

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用，即某一项或多项目标的实施可能对其他目标具有正面或负面的影响，具体可分为协同（一个目标的发展促进另一个目标的发展）和权衡关系（一个目标的发展限制另一个目标的发展）。例如，为满足全球人口增长对食物的需求（SDG 2：零饥饿）所采取的耕地扩张和集约利用等手段，会带来一系列的区域水资源安全问题（SDG 6：清洁饮水和卫生设施）和生态问题（SDG 15：陆地生物），并通过生物物理和化学过程影响局地 and 全球气候（SDG 13：气候行动）。因此，充分认识不同目标间的协同和权衡关系，对于实现全部目标的共同发展具有重要意义。

目前，联合国各相关部门和机构采用各成员国上报的数据，针对全部或不同专题目标开展了大量国别水平的监测和评价研究。例如，联合国粮农组织（FAO）对粮食安全相关的 21 项指标进行评价，发现全球粮食及农业生产领域的进展仍然不足，2030 年 SDG 2 将难以实现^[1]；联合国水机制（UN-water）的报告也指出 SDG 6 水安全目标的实现将较为困难^[2]；联合国可持续发展解决方案网络（UNSDSN）制定了用于国家层面的 SDGs 综合评价标准^[3,4]，为各国横向比较提供了依据。然而，这些工作均针对单个或多个目标进行评价，缺乏对于多个目标间关系的分析。

联合国环境规划署（UNEP）在 2021 年发布了环境类指标与其他指标交叉分析报告《环境与可持续发展目标进展评估报告》（*Measuring Progress: Environment and the SDGs*）^[5]，介绍了 92 项与环境相关的 SDG 指标，并采用相关性分析对环境状况和变化驱动因素/社会状况相关指标的关系进行定量分析。该报告还强调了分析环境相关数据和理解环境社会经济相互作用对于全面实现 SDGs 的重要性。除了官方报告外，许多科学家也探索了不同区域、不同专题 SDGs 协同和权衡关系。但截至目前，仍缺乏对 SDGs 协同和权衡关系的系统性认识^[6]，特别是对于

数据瓶颈问题及地球大数据支撑这一问题发挥的作用仍不清楚。

本文旨在梳理目前 SDGs 协同和权衡的最新研究进展和主要发现，进而围绕地球大数据在支撑 SDGs 协同和权衡研究中的应用潜力进行深入剖析，展望并提出优化 SDGs 协同发展路径的地球大数据支撑方案。

1 SDGs 协同与权衡的研究进展

1.1 全部 SDGs 关系的综合分析

SDGs 协同与权衡研究方法可以分为基于专家知识的定性评价、基于统计数据的相关分析和基于地球大数据的定量分析 3 个方法或阶段。Nilsson 等^[7,8]提出了一个用于描述 SDGs 间相互作用的框架，该框架的核心是将相互作用分为 7 个等级——不可分割型（Indivisible）、增强型（Reinforcing）、适应型（Enabling）、一致型（Consistent）、约束型（Constraining）、抵消型（Counteracting）、消除型（Cancelling），并根据专家知识定性地刻画一个目标与另一个目标变化间的关系。该框架强调关键环境影响因素，包括地理环境、管理水平、实施技术和政策、时间范围等。该框架还强调相互作用的方向性，包括单向（如电力供应和教育）和不对称双向（如卫生和农业生产），进而产生积极或消极的反馈循环。Weitz 等^[9]将该方法应用于国家层面的评价，在 SDGs 交叉影响矩阵中使用 7 分制对目标相互作用进行了评分。在完成二元关系矩阵之后，利用网络理论和系统分析得出哪些目标对其他目标最有影响。Fu 等^[10]从系统的角度出发，将可持续发展视为整个人类社会共同合作的产物，并将 17 个 SDGs 分为“基本要素”“目标”和“治理”3 个大类。该研究认为通过实施有效的治理措施，可以实现基本需求的最小化和预期目标的最大化；同时，为了保障各项目标的落实，促进不同层级政府和管理部门之间政策一致性的

实现,也需要深入分析各个分类内部各项目标和具体目标的关系。

尽管上述研究框架实现了所有 SDGs 相互作用的评价,但该类研究缺乏定量化的分析。Pradhan 等^[11]利用联合国统计司(UNSD)提供的 1983—2016 年覆盖全球 227 个国家的 122 个指标的时间序列数据,在全球和国家的尺度上,对近 30 年来所有 SDGs 目标间和目标内不同指标间的协同和权衡关系进行了

定量分析(图 1)。结果表明,从全球来看,绝大多数国家都表现出 SDGs 间的协同关系多于权衡关系的特点,这为 SDGs 成功实施提供了牢固的基础。特别是 SDG 3(良好健康与福祉),在大多数国家都与其他目标间存在较强的协同关系。而对于权衡关系来说,大多数国家都表现出 SDG 3 与 SDG 12(负责任的消费和生产)、SDG 3 与 SDG 15(陆地生物)间的权衡关系。这表明,在大多数国家,人民生活水平的提升往往伴随着生态系统的退化^[11]。在此研究基础上,Warchold 等^[12]采用了更新和更高覆盖度的数据(1991—2019 年,247 个国家的 171 个指标)进一步分析了全球和国家层面 SDGs 间和 SDGs 内不同指标存在的线性或非线性的协同和权衡关系。结果同样表明,无论在各 SDG 的内部,还是 SDGs 之间,协同关系都多于权衡关系。此外,该研究还发现 SDGs 各目标间的协同和权衡关系在不同的人群、收入群体及地域之

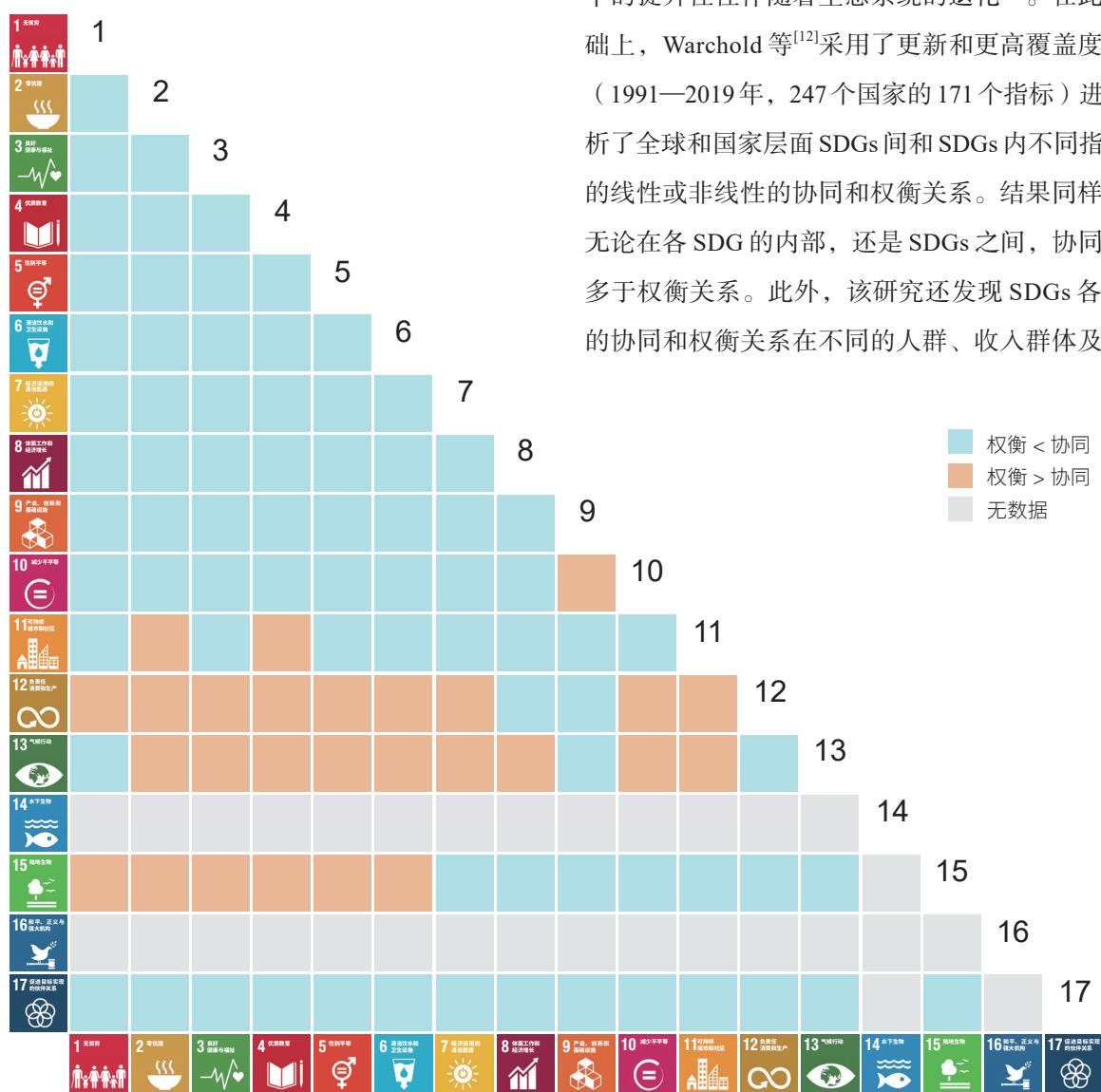


图 1 全球 SDGs 多目标权衡与协同关系综合分析

Figure 1 Global analyses on synergies and trade-offs of different SDGs

数据来源于 Pradhan 等^[11]

Refer to Pradhan et al.^[11]

间存在较大的变化。

上述基于统计数据和相关分析的方法也被应用于特定国家的系统分析。例如，Ramos 和 Laurenti^[13]采用 UNSD 收集的 231 个 SDG 指标数据研究了 2000—2019 年西班牙全部 SDGs 协同和权衡关系。该研究发现 80% 的 SDG 指标间都存在着显著协同或权衡关系；其中，SDG 4（优质教育）、SDG 5（性别平等）、SDG 7（经济适用的清洁能源）这 3 个目标下指标的协同关系最强，而 SDG 1（无贫困）、SDG 2（零饥饿）、SDG 6（清洁饮水和卫生设施）、SDG 8（体面工作和经济增长）这 4 个目标间协同关系表现较弱。

1.2 典型 SDGs 关系分析

基于联合国统计数据分析，也可针对典型主题识别出部分 SDGs 的协同或权衡关系。对于 SDGs 目标间的协同关系，Pradhan 等^[11]研究表明 SDG 1 和其他目标间的协同关系最多，其次是 SDG 3。相反，SDG 12 和 SDG 15 与其他 SDGs 间的权衡关系最多。Warchold 等^[12]也发现 SDG 1、SDG 4—6 与大多数的 SDGs 间都存在较强的线性协同关系，表明这 4 个 SDGs 的提升会促进其他 SDGs 成比例的发展；而 SDG 3 和 SDG 7 与其他 SDGs 间存在较强的非线性协同关系，表明 SDG 3 和 SDG 7 的提升引起其他 SDGs 不成比例的发展。对于权衡关系来说，SDG 2 和 SDG 17（促进目标实现的伙伴关系）与其他 SDGs 间存在着较强的线性权衡关系，表明这 2 个目标和其他大多数 SDGs 都处于竞争性的关系。除了采用统计数据开展的 analysis 外，多源数据的应用也为认识 SDGs 协同与权衡关系提供了重要支撑。例如，Vijay 和 Armsworth^[14]利用全球农田分布数据、自然保护区数据，以及物种分布和生物群落数据等，分析了 SDG 2 和 SDG 15 之间的相互关系。其研究发现全球在自然保护区内部有 $1.4 \times 10^6 \text{ km}^2$ 的农田，占自然保护区总面积的 6%；特别是在热带和亚热带地区，由于粮食安全风险程度较大，保护区内存在较多的农田，

且该部分农田还在持续扩张（对应 SDG 2），从而对当地的生物多样性保护（对应 SDG 15）造成了较大的威胁。

在 SDGs 各目标间的相互关系中，目前对特定专题关联机制的研究较多。例如，粮食（SDG 2）—能源（SDG 7）—水（SDG 6）是被广泛关注的研究议题之一^[15-21]。尽管过去几十年间全世界的生活水平取得了巨大的进步，但截至 2015 年，世界上仍然有 6.6 亿人口缺乏安全的饮用水、24 亿人口缺乏良好的卫生服务、8 亿人口面临长期的食物短缺、12 亿人口没有用上电^[19]。粮食、能源、水之间除了相互作用，也对其他的 SDGs 产生了一定的影响。例如，Fader 等^[21]发展了一种评估 2 个 SDGs 间协同和权衡关系的方法，对 SDG 2、SDG 6、SDG 7 所有指标间存在的两两协同和权衡关系进行了分级，发现指标对之间不存在严重的权衡关系：在所有的两两指标组合中，有 166 个组合表现出协同关系（其中 59 个组合表现出极强的协同关系），而仅 26 个组合表现出轻微的权衡关系。此外，该研究证实 SDG 6 与其他目标间的协同关系程度最大，这表明了实现水资源安全会使得实现其他 SDGs 变得更为容易。举例来说，在水—能源相互作用中，有效的节水措施会减低处理污水而产生的能源消耗^[19]；而在水—粮食相互作用中，水资源安全是农业可持续发展的基础。在对粮食—能源—水这一典型 SDGs 目标关联分析基础上，国内外一些研究团队尝试在该系统中加入新的目标来实现该系统内 SDGs 多目标的协同优化^[18,22,23]。例如，Salah 等^[22]研发出了一种基于太阳光—温室气体—海水净化的农业灌溉系统，成功为粮食—能源—水—气候变化之间的协同提供了典型实施案例。

尽管粮食、能源和水目标间的关系以协同为主，但 SDG 2 各项指标与其他 SDGs 的权衡关系不容忽视。因为与粮食有关联的各项指标都要严重依赖能源的使用，而可持续性使用其他能源，就不可避免地会

与能源相关各项指标的发展产生冲突。举例来说，粮食生产不仅需要大量的灌溉用水，而且需要大量的燃油等能源支持。又如，在粮食安全（SDG 2）—气候变化（SDG 13）—生物多样性（SDG 15）之间的权衡方面，Hinz 等^[24]利用 RCP8.5 未来气候情景^①数据、SSP2 未来社会经济情景^②及土地利用数据等，通过农产品贸易政策分析国际模型（IMPACT）模拟了未来情景下印度农业生产的变化。结果表明：2030 年以前农田扩张（对应 SDG 2）会占用大量的生态用地，进而带来生物多样性的下降；同时也会使得陆地碳储量发生变化（对应 SDG 15），进而影响当地的气候变化（对应 SDG 13）。这些模拟预警研究对于认识 SDGs 间权衡关系，实现区域 SDGs 协同发展具有重要指导意义。

1.3 单 SDG 内子指标间关系分析

Pradhan 等^[11]对各国的单个 SDG 内各项指标间的相互关系分析表明，SDG 内部各指标间的协同关系多于权衡关系。这对 SDGs 的实施是一个积极的信号，暗示了指标间的关系更倾向于相互配合，而非竞争。尤其对于 SDG 1、SDG 3、SDG 4、SDG 10（减少不平等）、SDG 12、SDG 13 内部各指标间的协同关系占到 80% 以上；而 SDG 7、SDG 8、SDG 9（产业、创新和基础设施）、SDG 15 内部指标间的权衡关系较多。还有一些 SDGs 目标内部指标间同时存在协同和权衡关系^[11]。

此外，某 SDG 内各子指标间也可能存在非线性的协同关系。以 SDG 3 为例，根据 Kapur^[25]研究，过去几十年间在全世界范围内实施的预防和控制非传染性

疾病措施，即 SDG 3.4.1（心血管等非传染性疾病导致的死亡减少 1/3），极大地改善了产妇的健康水平，很大程度推进了 SDG 3.1.1（孕产妇健康）向前发展。而这种关系是非线性的，即 SDG 3.4.1 和 SDG 3.1.1 之间呈现了不成比例的关系。

综上，目前已有的研究主要利用基于专家知识的定性或半定量分析、基于统计数据的相关分析等方法评价不同目标之间的关系，但是这些研究仍存在一定的不足：① 基于专家知识的定性或半定量方法，对于专家的主观性判断有较强的依赖性；② 由于各国使用的统计数据存在差异性和质量等问题，使得统计分析方法也具有误差。

2 地球大数据支撑 SDGs 协同与权衡的前沿进展

2.1 SDG 指标数据的不足

（1）SDG 指标数据缺乏严重。《2020 年可持续发展目标报告》指出，数据可获得性的不断改善，为实现国别对比提供了更多的支持。然而，在空间范围、数据质量、数据时效性和数据粒度等方面仍存在较大的改进空间。《2030 年可持续发展议程》也指出当前一半以上的 SDG 指标没有数据支撑，而指标数据的严重不足是 SDGs 评估面临的主要挑战之一。比如，SDG 指标数据库^③目前覆盖 346 个区域，有 563 个指标，时间跨度为 2000—2021 年。但是，该数据库中至少一半的国家自 2016 年以来的 SDG 1 数据不可获取，只有 93 个指标达到 Tier I 的标准^④。SDGs 技术促进机制目前最紧迫任务是实现对 Tier II 和 Tier III 数据

① Representative Concentration Pathways (RCPs) 为政府间气候变化专门委员会 (IPCC) 确定的代表性浓度路径，其中 RCP8.5 为在无气候变化政策干预时的高端浓度路径。

② Shared Socioeconomic Pathways (SSPs) 为共享经济路径，是 IPCC 在 RCPs 情景基础上定量描述气候变化与社会经济发展之间关系的多个路径，其中 SSP2 为中间路径。

③ <https://unstats.un.org/sdgs/indicators/database>。

④ Tier 分类用于表征各可持续发展指标监测评估方法和数据状态：Tier I 为指标定义清晰、有明确的计算评估方法，兼具有效的监测评估数据；Tier II 为指标定义清晰、有明确的计算评估方法，但还缺乏监测评估数据；Tier III 为指标还没有国际上确定的方法或标准。

指标的突破。

(2) 各国 SDG 指标数据的规范性和质量难以保证。世界各国由于自然条件和发展水平的差别, SDG 指标数据统计口径及概念均存在显著的差异。在评价体系的构建与区域评价上, 评价指标的差异给国家间 SDGs 对比带来了难度, 数据规范性有待提升。此外, 由于 SDG 指标数据量较大并依赖于官方统计, 数据的客观真实性在个别地区难以保证^[26]。个别 SDG 指标数据涉及国家政府部门的隐私、机密等敏感性问题, 无法公开获取。实现 SDG 指标数据统计的全球规范化, 畅通 SDG 指标数据获取渠道, 在实行必要的隐私、机密保护措施前提下尽可能增强 SDG 指标数据应用过程和目标的透明性, 是各国政府促进 SDG 指标数据共享战略必须解决的首要问题。Stokstad^[27]建议针对不同尺度区域合理设置各环境 SDG 指标阈值, 如明确某城市缺水人数的降幅、某国可再生能源的增幅等。因此, 在尊重各国家或地区差异的前提下, 应注重指标相对变化的情况而不是仅仅关注指标的绝对变化, 应设置

符合区域实际情况的合理区间。

(3) 个别 SDG 指标数据难以量化。根据 Stokstad^[27]的研究, 在 169 项 SDGs 具体目标中, 仅有 29% 被明确定义并易于监测, 而 54% 的具体目标存在措辞模糊、难以度量等问题, 其余 17% 更是缺乏科学依据和政策价值。尤其是在环境指标方面, 如 SDG 6.4 (大幅减少缺水人数)、SDG 7.2 (大幅增加可再生能源在全球能源结构中的比例) 等不少具体目标缺乏明确的量化要求, 给目标评价、比较和最终实现带来一系列难题。

2.2 地球大数据为 SDGs 评价带来新的机遇

17 个 SDGs 中, 多个目标与地表覆盖和环境紧密相关, 如 SDG 2、SDG 6、SDG 11 (可持续城市和社区)、SDG 13、SDG 14 (水下生物) 和 SDG 15。对地观测技术近年来取得快速发展, 集卫星观测、近地面观测和地面调查等方式融合的地球大数据具有海量、多源、多时相等特征, 为 SDGs 评价提供了重要的数据和技术支撑 (图 2)。地球观测数据和地理信

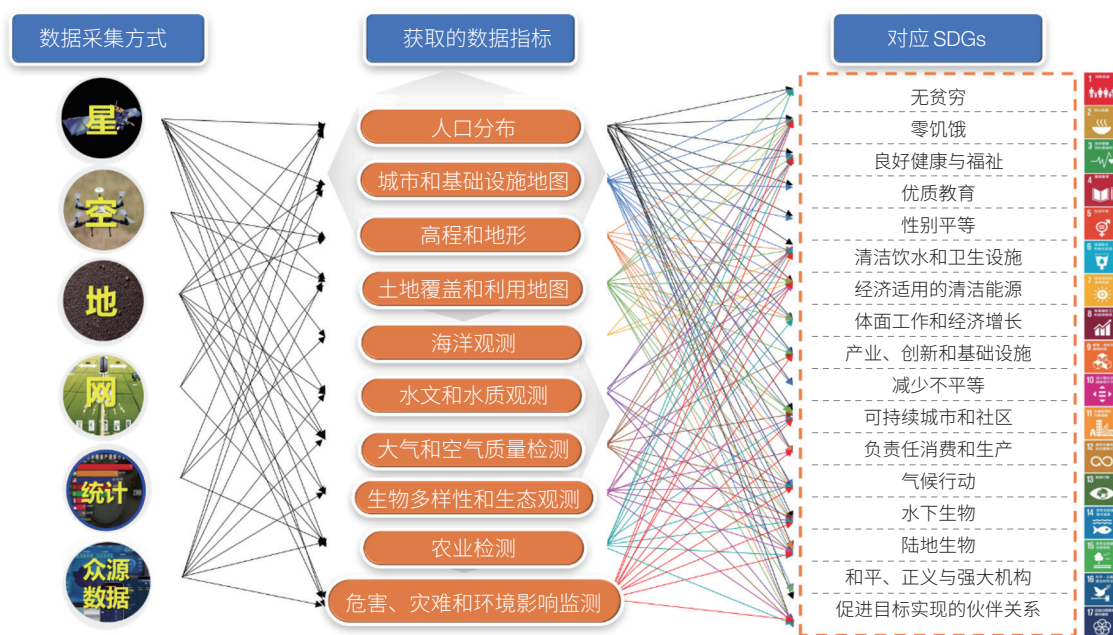


图 2 地球大数据获取专题数据并支撑 SDGs 的简要思路框架

Figure 2 Framework of Big Earth Data in support of thematic indicators and SDGs

数据指标与 SDGs 的对应关系参考自文献 [29]

Corresponding relationship between data indicators and SDGs is based on Ref. [29]

息数据可以为传统官方统计数据提供重要补充或替代,其连续的空间和时间覆盖可以在SDG指标监测中及时捕捉地表要素的变化,克服统计数据在不同国家的标准和质量不统一等问题。联合国官方统计大数据全球工作组也在探索利用对地观测数据估算官方统计数据以改进可持续发展指标评价的潜力^[28]。调查表明,卫星图像在提高统计结果时效性、减少调查频率、减少费用等方面有很大帮助。

多个地球观测组织已经致力于对地观测在SDGs中的应用研究。例如,地球观测组织(GEO)于2017年发布了《地球观测支持〈2030年可持续发展议程〉》(*Earth Observation in Support of the 2030 Agenda for Sustainable Development*)报告,强调了地球观测技术在支持SDG指标框架方面的重要作用,并报告了几项交叉综合性的示范案例^[29]。GEO下属的全球农业监测计划(GeoGLAM)依靠各种不同时空分辨率的卫星数据实现了作物产量及天气预测,监测全球耕地和牧场以改善粮食生产。基于卫星观测获取的细颗粒物(PM_{2.5})和可吸入颗粒物(PM₁₀)浓度的年平均值(对应SDG 11)与卫生健康(对应SDG 3)之间的因果关系分析,也为城市空气质量决策提供了支持。此外,欧洲航天局(ESA)于2018年发布《支持可持续发展目标的卫星地球观测》(*Satellite Earth Observations in Support of the Sustainable Development Goals*),对使用地理信息技术及卫星数据支持SDGs实现,从相关地表参数数据获取、反演和统计分析等方面进行了介绍^[30],并针对卫星数据结合统计数据开展SDG指标的综合分析介绍了一些案例。中国科学院于2018年启动了战略性先导科技专项(A类)“地球大数据科学工程”(CASEarth),为SDG指标监测和评价提供了重要的数据支撑。CASEarth根据地球大数据的优势和SDG指标体系的特点,遴选出6个SDGs中的20个指标进行剖析,以期对11%的Tier II和10%的Tier III指标作出实质贡献。

对地观测技术可提供包括水、土、气、生、人等在内的多主题信息,并具有很强的时空连续性。这些信息将提升地方、国家、区域和全球各级及跨部门的监测能力,并且降低监测成本,让各国政府能够在有限资源范围内完成SDGs进展的评价^[28]。一个典型的地球大数据应用案例是中分辨率光学遥感的发展和应用。自2008年美国陆地卫星(Landsat)系列存档数据免费共享以来,中分辨率光学遥感取得了快速发展。Landsat具有16天重访周期,形成了自20世纪80年代以来对地表的连续观测;欧洲航天局哨兵2号卫星(Sentinel-2)在光谱、空间和时间分辨率方面较Landsat均有提升,能够实现5天间隔的10—20 m分辨率的观测,其携带的新的红边波段等为地表植被和农业监测提供了新的数据源^[31];我国高分系统卫星也取得了重要进展,特别高分6号和高分1号卫星组网运行后,数据获取时间由4天缩短到2天,并在农业监测、森林调查、防灾减灾等领域发挥重要作用。这些数据的融合能够更大程度地提升数据的时空分辨率,实现对资源环境相关SDG指标的更高精度观测^[32,33]。

2.3 地球大数据支撑SDGs协同与权衡的最新进展和案例

在所有SDG指标中,Tier II或Tier III指标尚未形成明确的概念或标准,缺乏统计数据。地球大数据为缺乏统计数据的指标提供了重要的数据来源,特别是多源遥感数据和社会众筹数据等多种数据形成的科学大数据^[34],为进一步理解多目标间的协同和权衡关系提供了保障。已有研究表明,遥感可以为至少33个指标提供直接的支持,特别是SDG 6^[35,36]、SDG 11^[37]、SDG 14和SDG 15^[38,39]。当然,也存在3个地球观测难以提供直接支持的目标,包括SDG 4、SDG 8和SDG 10。但是,即使不能对这3个目标提供直接支持,遥感观测仍然通过人口分布、城市结构等来间接服务于上述目标的评价^[37](图2)。

尽管地球观测实现单 SDG 或子指标评价的研究较多^[35,36,38-42]，但地球大数据支撑多 SDGs 协同和权衡研究的案例较少，这在一定程度上反映了该方向未来研究潜力较大。在此，我们以印度西北部典型农业区旁遮普邦和哈里亚纳邦为例，利用遥感提取的水稻种植面积、陆地水储量数据（TWS）、空气质量数据（PM_{2.5}和气溶胶光学厚度）、农田秸秆焚烧面积等数据进行分析，发现卫星观测可以有效支持对印度西北部粮仓粮食—水—空气相互作用关系的了解（图3）^⑤。基于多源卫星观测结果，我们发现2001—2018年该地区水稻种植面积扩张引发地下水枯竭，同时秸秆燃烧增加进一步加剧了空气污染，这揭示了水稻扩张对地下水枯竭、区域空气污染和公共健康的影响机制。2009年印度实施了地下水保护政策，卫星观测结果显示政策实施后这些相互作用发生了变化，主要表现为由于水稻种植和收获时间推迟，地下水耗水量减缓，但空气污染加重造成公共健康形势恶化。该分析基于遥感监测的客观数据实现了对SDG 2、SDG 3、SDG 6和SDG 11之间相互作用关

系的认识，展示了遥感数据和方法在跟踪 SDGs 实施进展和为现有 SDGs 挑战寻求解决方案方面的应用潜力^⑤。

3 地球大数据支撑 SDGs 协同与权衡的展望

SDG 指标体系的设立为联合国层面评估各国 SDGs 完成进度提供了定量的评价参考。在全球和国别层面，联合国各机构组织、其他非政府组织和学者等已经开展了不同领域及综合性的 SDGs 评估研究。但由于数据缺失、数据不匹配等诸多因素，区域尺度上 SDGs 协同和权衡的工作还相对较少。因此，需要结合不同区域在 SDGs 实现过程中存在的问题，开展个性化的 SDGs 协同和权衡研究，并抽象不同的综合评估范式为同类型区域提供示范参考。

地球大数据具有高时空覆盖、更新速度快、数据客观等特点，在实现国别间数据一致性和透明性等方面发挥重要作用，使得其成为分析 SDGs 目标间关系的重要支撑。2018年以来CASEarth对6个SDGs开展了一系列工作，针对指标的数据和模型方法的不确

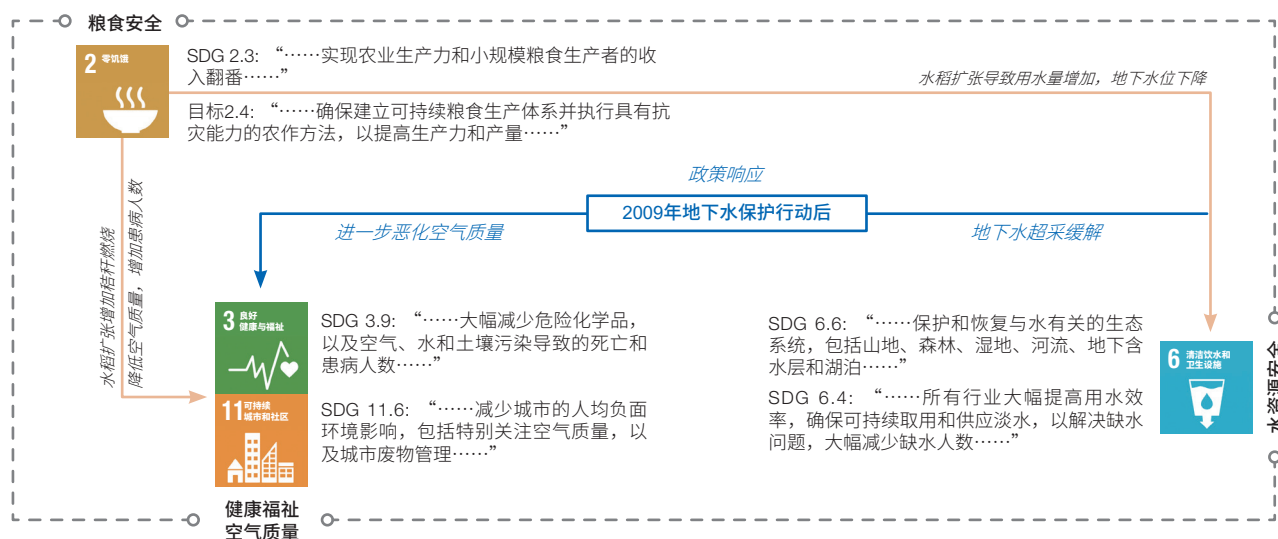


图3 印度西北部粮食—水—空气—健康相关 SDG 目标的协同与权衡关系^⑤

Figure 3 Synergies and trade-offs of SDGs 2, 3, 6, and 11 involved in food–water–air–health nexus in Northwest India^⑤

⑤ Singha M, et al, Satellite evidence on the trade-offs of the food–water–air quality nexus over the breadbasket of India. Global Environmental Change–Human and Policy Dimensions. In revision.

定性开展了深入探索,为减少联合国各成员国提交的非约束性评估指标的不确定性提供了重要的借鉴和参考^[43]。针对未来地球大数据支撑SDGs多目标权衡和协同的研究,在此提出3点展望。

(1) 完善地球大数据支撑SDGs协同与权衡的理论和方法体系,构建运行平台和综合模型,实现对SDGs协同和权衡关系的实时监测和预警。运行平台的建立将为推进我国SDGs实现提供重要支持,有助于及时掌握SDGs目标间的权衡状态^[44]。例如,我国改革开放以来经济快速发展的同时,一系列的生态系统退化问题逐渐凸显。尽管大规模生态恢复工程的实施^[45]极大地改善了区域生态环境,并提升了经济、生态协同发展水平;但个别地区的生态保护、荒漠化等问题仍需科学的监测和治理,不同地区间的权衡问题依然存在^[46]。构建一个地球大数据支持的SDGs综合模型和运行平台,并模拟多种政策对SDGs目标间、区域间的协同和权衡关系,实现实时监测和预警,对于实现SDGs具有重要的理论和现实意义。

(2) 加强不同领域专家的合作研究,通过跨领域的合作进一步提升多SDGs协同和权衡研究的水平。农业、生态、经济、城市、水文、健康等领域专家分别聚焦SDG 2、SDG 15、SDG 8、SDG 11、SDG 6、SDG 3等目标,但跨领域的合作仍然相对有限,这在一定程度上制约了对SDGs协同和权衡的深入理解。傅伯杰^[47]提出了以地理学综合视角采用“分类—统筹—协作”的方法来推进SDGs实现的框架思路,为整体推进实现SDGs提供了重要理论依据。此外,与联合国前期的千年发展目标(MDGs)不同,SDGs明确地呼吁各国政府、私营部门和民间社会共同行动起来以应对可持续发展的挑战。比如,当企业被赋予了重要使命,有利于激发企业的应用创新解决方案及技术活力,共同面对可持续发展挑战^[48]。

(3) 通过大数据、云计算等技术创新推动SDGs协同和权衡的深入认识和实践应用。对地观测数据为

可持续发展研究提供了大尺度、高质量、无偏差的数据,是大量SDG指标的数据来源,如森林覆盖率(SDG 15.1)^[38]、土地退化(SDG 15.3)^[49]、作物面积和产量(SDG 2.4)等^[42,50]。近年来,云计算平台的快速发展为对地观测数据的广泛应用开辟了新的范式。例如,目前已经出现了全球森林^[51,52]、水体^[53-55]、耕地^[56]、城市^[57]、碳循环^[58-60]、生物多样性^[61,62]、全球城市可达性^[63]、人类健康^[64,65]、贫困^[66,67]等多个主题的数据集,这些高精度空间数据产品的出现为SDGs协同和权衡研究提供了可靠的数据支撑。特别是多源遥感数据及大数据的发展,使得更为客观的SDG指标评价及协同权衡分析成为可能。但这些创新技术为SDG指标评价研究提供更丰富的数据的同时,数据的质量和验证也应受到更多的重视。

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Big Earth Data Supports Synergies and Trade-offs of Sustainable Development Goals: Progress and Prospect

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Abstract The United Nations Sustainable Development Goals (SDGs) are an important guide for different countries and regions to achieve sustainable economic, social, and environmental developments. They include 17 goals and 169 specific targets. The interactions among the goals can be manifested as synergy or trade-off; that is, implementing one or more goals may positively or negatively affect other goals. At present, important progress has been made in the monitoring and evaluation of individual goals. However, our understanding of the synergies and trade-offs among multiple SDGs is still limited. Firstly, this paper describes the current progress in the synergy and trade-offs of SDGs from three aspects: comprehensive analyses of all the SDGs, thematic analyses of few relevant SDGs, and the relationship of the specific indicators under certain SDG. Secondly, in view of the data bottleneck in the current studies, combined with the latest progress of the Big Earth Data, this paper showcases the typical scenarios of the Big Earth Data supporting studies of the synergy and trade-off of SDGs. Thirdly, the Big Earth Data's potential and future research prospects on the synergies and trade-offs of SDGs are proposed. This study shows that SDG synergy and trade-off analyses have experienced three stages: a semiquantitative evaluation based on expert knowledge, correlation analyses based on statistical data, and quantitative analyses based on the Big Earth Data. Different data sources from different countries could lead to varying results, and the Big Earth Data plays a vital role in promoting data consistency and transparency between countries. Therefore, it provides crucial support for the understanding of synergies and trade-offs of SDGs. The purpose of this study is to summarize the latest progress of synergy and trade-off studies of SDGs, which has received less attention in SDG-related research, and to support decision making for realizing the economic, environmental, and social goals together.

Keywords Big Earth Data, sustainable development goals (SDGs), synergy, trade-off



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