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农业适应气候变化研究进展回顾与展望*

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摘 要: 气候变化对农业生产产生了广泛而深刻的影响。本文基于气候系统和农业生态系统、经济社会系统的相互作用关系, 梳理气候变化的农业影响和适应的逻辑层次。影响的逻辑层次可以归结为: 气候平均状态变化的影响、极端天气气候事件加剧的影响、气候变化引起的生态后果和经济社会后果等 4 个方面; 与气候变化影响的逻辑层次相应, 适应气候变化的逻辑层次可以分解为: 气候变暖条件下农业气候资源的高效利用; 根据气候变暖背景下农业气象灾害发生新特征, 系统调整农业防灾减灾工作思路与技术路线; 加强农业生物多样性保护, 优化农业生态系统的结构与功能, 充分发挥农业生态系统服务增强农业气候韧性; 以及农业经济社会系统整体的优化转型。在对气候变化影响评估和已采取的适应措施系统总结回顾基础上, 分析了农业适应气候变化面临的挑战, 即: 气候胁迫不断加大、农业系统对于气候变化的脆弱性不断加大、粮食安全保障体系还很不完善、适应能力薄弱等。最后提出农业适应气候变化需要加强研究的关键科学问题: 扩展气候变化农业影响评估研究领域、科学辨识农业之于气候变化的脆弱性和风险、揭示农业适应气候变化的科学机理、构建农业适应气候变化技术体系、加强农业适应气候变化的决策能力研究、加强农业适应行动实施的保障能力研究等。

关键词: 农业; 适应气候变化; 逻辑层次; 生态系统服务; 粮食安全

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Review on the research progress of agricultural adaptation to climate change and perspectives*

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Abstract: Agricultural production has been widely and seriously affected by climate change. In this paper, the logical layers of climate change impacts and adaptation were synthesized based on the interactions of climate system and agricultural ecosystem as well as the social-economic system. The logical layers of climate change impacts could be clarified as the effects due to the change of climate average trend, the enhanced extreme climatic events, ecological consequences and social-economic consequences, then the logical layers of adaptation could be clarified as the high-efficiency use of agro-climatic resources due to warming, systematically adjusting the strategy and technical approaches for disaster reduction and prevention according to the new features of enhanced agro-meteorological disasters, increasing the agricultural climate resilience with the well employment of ecosystem services through the protection of agro-biodiversity and optimizing the agricultural ecosystem's structure and functions, and transformational update of the agricultural social-economic system. The challenges of agricultural adaptation to climate change were synthesized based on the sys-

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tematic review of the research progress on the already occurred climate change impacts and the adopted adaptation measures that the climatic stress onto the agricultural system is incessantly enhanced, the vulnerability to climate change is continuously increased, the guarantee system for food security is not complete yet, and the adaptive capacity is still very weak. Finally, the key scientific questions for agricultural adaptation were proposed to enlarge the aspects of climate change impacts assessment, to scientifically identify the vulnerability to climate change and the future climate risk, to reveal the theoretical mechanism of adaptation, to construct the agricultural adaptation system, to strengthen the research on how to increase the capacity of agricultural adaptation decision as well as the implementation of agricultural adaptation actions.

Keywords: Agriculture; Climate change adaptation; Logic layers; Ecosystem services; Food security

农业的生产对象是生物体, 其直接暴露在气候环境的胁迫之下。自工业化以来, 人为排放的温室气体 (GHGs) 急剧增加, 大气中 GHGs 浓度不断升高, 增强的温室效应引起气候变暖; 而大气太阳辐射强迫增加所产生的巨大能量积累, 引起极端天气气候事件频发、强度增大、影响范围扩大。2022 年长江全流域的高温干旱, 是气候变暖背景下极端天气气候事件加剧对农业生产和农业生态系统产生严重影响的典型案例。农业生产的气候高暴露性特征, 以及中国农业整体相对较低的生产力水平, 决定了农业是对气候变化高度敏感和脆弱的产业。气候变化对农业生产与粮食系统的影响是深刻而广泛的, 在当前日益严峻的气候变化挑战下, 采取强有力的适应行动是农业应对气候变化的必然选择。

农业适应气候变化, 首先需要认识气候变化对农业的影响。国际国内学者开展了大量的气候变化对农业影响的研究。已经开展的气候变化对中国农业的影响评估, 早期发表的文献主要集中在粮食作物生产和草地畜牧业, 评估气候变化对农业气候资源、耕地与土壤、环境、作物生育期、产量和品质, 以及种植制度与种植区域/种植格局、农业气象灾害、病虫害、农业与化肥用量等方面的影响[1-2]。随着气候变化对农业影响科学认识的深入, 研究领域扩展到经济作物、渔业、粮食安全 (粮食供给与需求、营养与品质、食物消费结构)[3-4]。以联合国粮农组织 (FAO) 发布的 The State of the World's Biodiversity for Food and Agriculture 报告[5] 为典型标志, 研究人员和社会各界愈益认识到加强生物多样性保护、提升农业生态系统服务[6] 对农业可持续发展的重要性。

本文首先基于气候系统和农业生态系统、农业经济社会系统之间的相互作用关系, 梳理气候变化影响与适应的逻辑层次, 按照影响的逻辑层次总结已经发生的气候变化对农业的影响及未来的气候风险, 按照适应的逻辑层次总结已经采取的适应措施, 然后分析存在的差距、问题与挑战, 提出未来需要加强研究的农业适应气候变化关键科学问题。

1 理论基础与方法

1.1 农业系统分类和相互作用关系

农业是国民经济的基础, 而粮食生产是农业部门的基本任务。保障粮食安全, 是《联合国气候变化框架公约》(UNFCCC, https://unfccc.int/) 确立的应对气候变化的三大战略目标之一, 其他两个目标, 即生态系统能够自然地适应气候变化、经济可持续发展, 也与粮食安全紧密相关。农业是一个"自然环境-生物-人类社会"综合交织、相互影响的复杂巨系统; 按照生产对象、投入水平、产品用途, 以及生产力水平、地域特征等有多种分类方式; 而从系统学的角度进行区分, 其自然属性为农业生态系统, 其社会属性可以分为农业经济系统、技术系统或生产子系统、管理子系统、科教子系统等。政府间气候变化专门委员会 (IPCC) 第六次评估 (AR6) 所发布的《气候变化与土地》特别报告 SRCCL[7], 总结了在粮食安全框架下粮食系统和气候系统、生态系统和社会经济系统之间的相互作用关系。本文的讨论将农业巨系统简化为自然生态系统和经济社会系统, 这两大类系统受气候变化的影响, 其相互作用关系如图 1 所示。

从图 1 可以看出, 气候与农业两个巨系统之间的相互作用关系为: 气候系统由于增强的温室效应产生额外的气候胁迫作用于农业系统, 而农业系统产生的 GHGs 排放又加剧气候变暖。农业巨系统还有一个方式作用于气候系统, 即通过改变局部环境的干预措施调节当地小气候, 从而减轻气候冲击, 如农田防护林网建设等。对于农业巨系统的生态系统, 包括农业自身的生态系统及与农业生产紧密相关的自然生态系统, 如授粉的昆虫、支持绿洲农业的冰川融水等。农业生态系统通过供给服务、调节服务、支持服务等作用于农业经济社会系统, 为人类提供食物、纤维、淡水、医药及其他工农业生产原料, 调节气候、维持大气化学的平衡与稳定、维持生命物质的生物地球化学循环与水文循环、养分循环、土壤形成与保持、生物防治和净化环境等。而当前

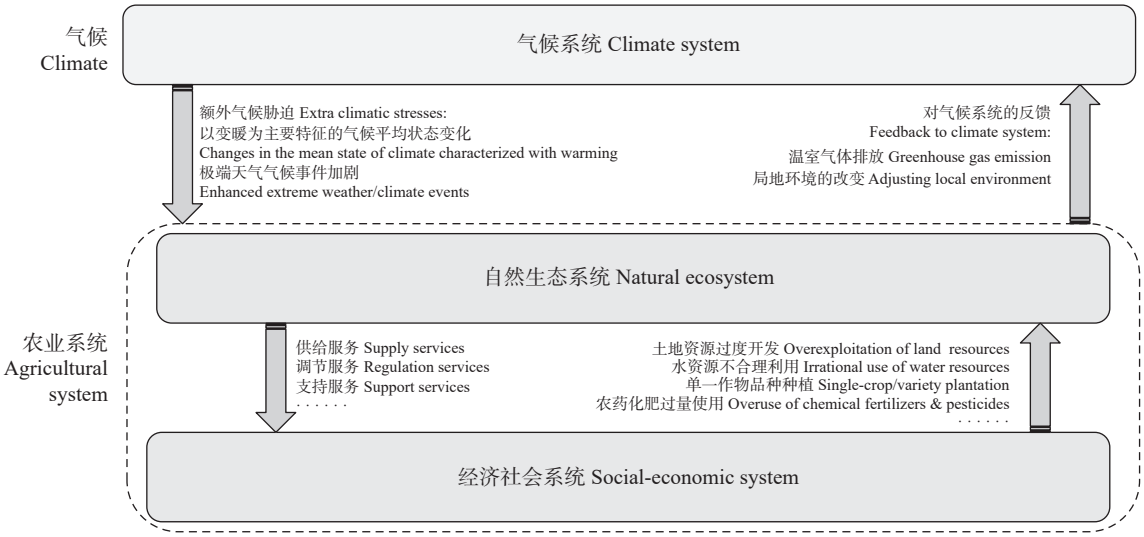

图 1　气候系统与农业系统相互作用关系

Fig. 1　Interactions of climate system and agricultural system

与农业相关的经济社会系统, 以异乎寻常的高强度胁迫作用于农业生态系统及与农业相关的自然生态系统。现代农业生产的高投入高产出生产模式, 农药化肥的过量使用、过度樵采、过度垦殖、过度放牧等, 导致土地退化、生物多样性减少, 生态环境严重恶化, 引发土壤板结、肥力下降、盐渍化、水体富营养化、地下水超采等一系列问题, 危及农业的可持续发展。

气候系统与农业生态、经济社会子系统是相互作用的。气候变化导致生态系统的服务功能降低, 需要更多的投入于农业生产以满足人类经济社会发展的需求, 而这反过来又进一步破坏生态系统的结构与功能, 形成恶性循环。农业是技术高度密集的产业, 通过采取积极主动的人为调控措施, 通过科技进步和科技创新, 改变当前农业高投入、高 GHGs 排放的生产模式, 实现气候变化条件下农业各子系统之间的良性互动, 是农业适应气候变化需要探讨的重大科学问题。

1.2　气候变化农业影响的逻辑层次

已经发表的论文和各种文献, 有关气候变化对农业影响的研究多是按农学分类进行总结的。如土壤的退化, 一个根本的原因是气候变暖加快土壤有机质的微生物分解, 加快养分矿化过程, 导致土壤有机质含量下降, 它实际上是气候系统和农业生态系统的相互作用问题; 再如农业种植结构调整, 首先是基于气候变暖导致的农业气候资源的改变, 但最终决定种植结构调整的驱动力则是经济社会的需求。图 1 所展示的气候系统和农业系统的相互作用关系, 为气候变化对农业影响的梳理总结提供了另一种思路, 即气候变化对于农业的影响机理, 一是增强的温室效应使气候系统产生额外的气候胁迫直接作用于农业生物体; 另一种则是气候胁迫和生态因素、经济因素一起作用于农业生物体所产生的一系列生态和经济社会后果。按照这样的思路, 气候变化产生的农业影响的逻辑层次如图 2 所示。对于气候系统的额外胁迫直接作用于农业生物体, 其平均趋势和极端天气气候事件的作用机理也是不一样的, 气候平均趋势的影响是整体上改变农业生物体适宜生长的气候条件, 而极端天气气候事件则是对农业生物体造成损伤, 其影响甚至是致命的; 而生态后果与经济社会后果, 由于各种因子交织在一起相互作用, 其后果更加错综复杂。

1.3　农业适应气候变化的逻辑层次

针对气候变化不同的影响层次, 其所采取的应对措施亦不相同。气候变化肇因于增强的温室效应, 因此, 减小气候系统所产生的额外胁迫强度, 可以减轻气候变化所产生的一系列影响的程度, 这就需要采取措施减少温室气体排放, 该方面的应对措施属于减缓范畴。而气候变暖已经发生, 今后还会持续和加剧, 则需要采取措施使农业系统与变化了的气候系统相匹配, 这属于农业适应气候变化研究的范畴, 是本文回顾与展望的重点。适应, 就其本质来讲, 就是农业系统对于实际的或预期的变化了的气候状态和影响所做出的一系列的趋利避害调整的过程[8]。不同层级的气候变化影响, 其适应的路径、方式不同。农业适应气候变化的逻辑层次如表 1 所示。可以看出, 对于气候平均状态的变化, 其表现为 CO_2 浓度升高、气候变暖、暖干化等, 这些影响之于农业

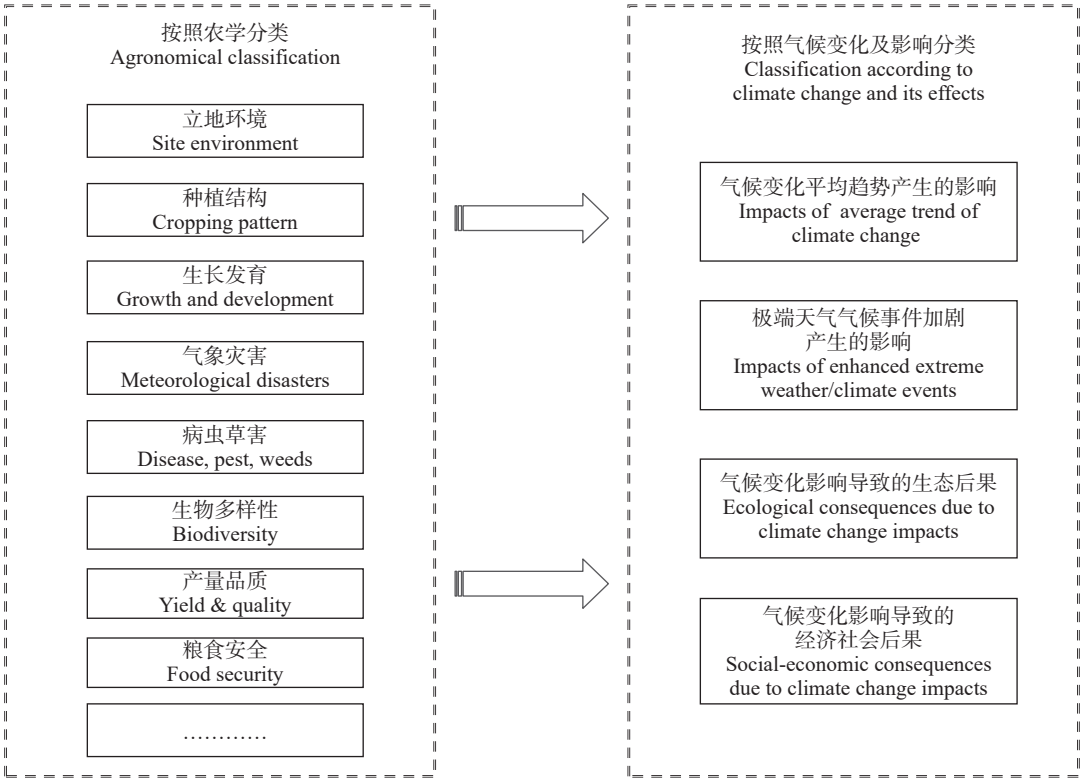

图 2 气候变化农业影响的逻辑层次

Fig. 2 Logical layers of climate change impacts on agriculture

系统, 其胁迫是长历时的; 究其本质, 其适应是农业生物体与变化了的气候条件的匹配问题, 是农业气候资源的高效利用问题。而对于加剧的极端天气气候事件, 其胁迫是对农业系统短历时的气候冲击, 表现为农业气象灾害加剧, 适应的着力点也是加强防灾减灾工作, 即根据极端天气气候事件发生的新特征, 对当前的减灾思路、减灾技术体系实现根本性的调整。之所以这么考虑, 是因为加强的温室效应在大气中、在地球上积累的能量巨大, 原有的措施很难抵御极端天气气候事件在短时间内释放的巨大能量对农业系统所造成的冲击。气候变化影响所带来的生态和经济后果则更加复杂。气候变化影响生态系统、经济社会系统的结构和功能。对于生态系统, 首先表现为生物多样性减少, 服务水平降低。因此, 生态系统适应气候变化, 首先是修复其自身的结构和功能, 提升生态系统服务功能, 支撑经济社会系统适应气候变化, 进而提升整个农业系统的气候韧性。气候变化对经济社会系统的影响, 则更由食物生产引申至加工、储存和消费等环节, 其适应的核心是保障粮食安全, 这就需通过适应性的管理实现资源优化配置、调整经济结构, 最终实现农业经济系统及其相关社会系统的全方位优化转型。

2 气候变化影响评估结论综述

本节基于图 2 所示的气候变化农业影响的逻辑层次, 系统总结气候变化农业影响方面的研究进展。本节的综述主要参考已经发布的气候变化国家评估报告[1-4] 及已经发表的文献[6,9-12]。表 2 的综述按照时间段分两个部分: 一是已经发生的气候变化的影响, 另一部分是未来气候变化的潜在影响。由于已经观测到的影响, 其气候值是“唯一”的, 其影响是在气候因素的胁迫之下采取各种调控措施后产生的结果, 因此, 观测到的影响是农业系统之于气候变化的脆弱性; 而未来气候变化的影响, 气候胁迫的强度取决于不同温室气体排放的路径, 因此, 其潜在的影响不是“唯一”的值, 取决于气候因素的胁迫强度和经济社会的发展水平, 故而称之为气候风险。

从表 2 的总结可以看出, 气候变化影响中国的农业生产的方方面面, 有些影响对农业生产是有利的, 如作物生长季普遍延长、作物适宜种植区扩展、种植结构的优化调整等。如果只考虑 CO_2 浓度升高, 有利于增强植物的光合速率和提高水分利用效率, 有利于农作物增产; 由于气候变暖, 在寒冷地区的热量资源增加, 使原来作物的不适宜区、次适宜区成为适宜区, 如东北水稻的大面积扩种、冬麦北移、

表 1　农业适应气候变化逻辑层次

Table 1　Logical layers of agricultural adaptation to climate change

影响层次 Impact layers	影响机制 Impacts mechanism	适应逻辑层次 Logical layers of adaptation
气候平均状态变化 Changes in average state of climate	CO_2浓度升高加速光合作用过程, 改变营养物质积累的进程; 气候的整体变暖, 影响农作物种植的空间分布乃至于农业生物体群落的结构变化和演替; 而暖干化则使作物种植向旱生化方向发展 The increased CO_2 concentration accelerates the photosynthesis process, and then changes nutrient accumulation of crops. The overall warming of climate affects the spatial distribution of cropping pattern, even the structural changes and succession of agricultural organism communities. However, warming and drying lead to crops to xerophilization	对于气候平均状态的改变, 适应的核心是农业气候资源的高效利用。气候的整体变暖, 合理利用则是资源; CO_2浓度升高加速光合作用、气候的暖干化趋势, 则需要培育高光效作物品种、培育耐旱作物品种 For the change of climate mean state, the core of adaptation is the efficient use of agro-climatic resources. The overall warming of climate is resources if rationally used. To respond to the accelerated photosynthesis due to increased CO_2 concentration as well as the warming and drying trend of climate, it is necessary to breed high photosynthetic efficiency crop varieties and drought-tolerant crop varieties
极端天气气候事件加剧 Enhanced extreme weather/climate events	高高温、低温、洪涝、干旱等极端天气气候事件对农业系统所产生的短历时气候冲击造成农业气象灾害加剧 The short-duration climate shock of extreme weather/climate events such as high temperature, low temperature, flood and drought on agricultural system has resulted in the intensification of agro-meteorological disasters	根据气候变暖背景下农业气候相关灾害发生新特征, 系统调整农业防灾减灾工作思路与技术路线 The strategy and technical route should be systematically adjusted according to the new features of agricultural climate-related disasters under the background of climate warming
气候变化引起的生态后果 Ecological consequence due to climate change impacts	气候变化改变生态系统的结构和功能, 导致土地退化与水土流失加剧、生物多样性减少、农业水生态水环境恶化; 海平面上升引起海岸侵蚀和咸潮入侵加剧, 海岸带湿地退化; 海水变暖导致的渔业资源分布的改变; 海水酸化引起珊瑚礁白化, 以及赤潮等海洋生物灾害加剧, 导致海洋生态系统退化 Climate change alters the structure and function of the ecosystem, leading to land degradation and soil erosion, biodiversity reduction, agricultural water ecology and water environment deterioration. The sea level rise leads to intensification of coastal erosion and salt tide intrusion, and degradation of coastal wetlands. Ocean warming induces distribution changes of fishery resources. Ocean acidification causes coral reef bleaching, and the aggravated marine biological disasters such as red tides, which will finally result in the degradation of whole marine ecosystems	加强农业生物多样性保护, 优化农业生态系统的结构与功能, 充分发挥农业生态系统的服务功能, 尤其是气候的调节功能, 为农业气候韧性增强提供自然属性的物质基础, 创造良好的减轻气候风险的生态环境 Strengthen the protection of agricultural biodiversity; optimize the structure and functions of agricultural ecosystems; give full play to the agricultural ecosystem services, especially the regulation service on climate; provide natural material basis for the enhancement of the climate resilience; and create a good ecological environment for mitigating climate risks
气候变化带来的经济社会后果 Economic-social consequence due to climate change impacts	气候变化改变农业优势产区和品质, 改变农产品生产和贸易格局; 极端气候事件导致局部粮食减产、加大供给与需求的不平衡、冲击粮食储备和运输设施安全等, 粮食安全风险加大 The advantageous production areas and quality of agri-products, as well as the pattern of agricultural production and trade were adjusted due to climate change. Extreme weather events lead to local grain production reduction, increase the imbalance between supply and demand, and impact the security of grain storage and transportation facilities, increasing the risk of food security	农业经济系统及其相关社会系统全方位的优化转型, 包括根据农业气候资源和气候相关灾害时空分布的改变调整农业基础设施建设布局, 建立完善的粮食安全社会保障体系, 完善体制机制与政策法规, 加强农业适应行动的管理与实施, 加强能力建设, 加强科技创新, 加强国际合作等 Comprehensive optimization and transformation of the agricultural economic system and its related social systems, including adjusting the layout of agricultural infrastructure in light of the temporal and spatial distribution changes of agricultural climate resources and climate-related disasters; establishing a sound social safeguard system for food security; improving institutional mechanisms, policies and regulations; strengthening the management and implementation of agricultural adaptation actions; and strengthening capacity building; promoting scientific and technological innovation and international cooperation

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表 2　已经发生的气候变化对农业的影响与未来气候风险

Table 2　Impacts of changed climate on agriculture and the climate risk in the future

影响层次 Effect level	已经发生的气候变化导致的农业脆弱性 Agricultural vulnerability induced by changed climate	未来气候风险 Future climate risk
气候变暖 Climate warming	●大气 CO_2 浓度上升, 作物的光合作用增强, 影响农产品产量和品质。气候变暖与 CO_2 浓度升高对品质影响因作物种类及品种而异, 如水果中的糖、柠檬酸、比黏度等有所提高, 高 CO_2 浓度会提高纤维长度, 棉花等以纤维为产品的作物品质有所提高; 对于粮食作物, CO_2 肥效作用总体上促进作物增产, 但由于植株中含碳量增加, 含氮量相对降低, 蛋白质含量降低, Fe 和 Zn 等元素含量下降, 总体上粮食作物品质下降 With the increase of atmospheric CO_2 concentration, photosynthesis of crops is enhanced, which affects the yield and quality of agricultural products. The effects of climate warming and rising CO_2 concentration on quality vary with crop types and varieties. For example, content of sugar and citric acid, and specific viscosity in fruits are increased. Fiber length also increases with higher CO_2 concentration, and this leads to higher quality of fiber-producing crops, e.g., cotton. For food crops, CO_2 fertilizer effect generally increases crop yield, but decreases overall quality of food crops due to the increase of carbon content and the relative decrease of content of nitrogen, protein, Fe and Zn in crops	●气候的持续变暖引起农业生物体物候的进一步改变, 作物种植进一步北移上扩, 复种指数进一步增加 The continuous warming of climate causes the further change of phenology of agricultural organisms, northward expansion of crop planting, and increase of multiple cropping index
	●气候变暖改变作物、牧草和果树物候期, 草原返青期、开花期总体呈显著提前趋势, 黄枯期不显著推迟, 生长季长度有延长的趋势, 长生育期作物品种种植有利于增产, 尤其在东北地区 Climate warming alters the phenological period of crops, herbage and fruit trees. The greening and flowering periods of grassland are significantly advanced with no significantly delayed yellow wilt period, and length of the growing season is extended. The planting of crop varieties with long growth period is conducive to yield increase, especially in Northeast China	●林果业优势产区进一步改变 The advantageous producing areas of forestry and fruit industry will be further altered
	●变暖使作物适宜种植区向高纬度、高海拔地区扩展, 作物熟制界限及热带作物种植界限北移, 复种指数增加。如水稻种植向北方扩展, 黑龙江水稻大面积扩种; 冬小麦种植北界北移西扩; 棉花主产区西移至新疆等 As a result of climate warming, the suitable planting area of crops expands to the high latitude and high altitude areas, the crop ripening limit and tropical crop planting limit move northward, and the multiple cropping index increases. For example, rice planting has expanded to the north, and rice planting in Heilongjiang has expanded in a larger area. The northern boundary of winter wheat expand to north and west. The main cotton producing areas moved westward to Xinjiang	●暖干化总趋势进一步加剧, 加重土地荒漠化、导致可耕地面积减少; 地表面水汽蒸发和植物蒸腾会增大, 农业水资源会更加紧张 The general trend of warming and drying is further intensified, which aggravates land desertification and leads to the reduction of arable land area. Soil evaporation and plant transpiration will increase, and agricultural water resources will be more strained
	●暖干化趋势加剧, 尤其是在华北、西南地区, 北方土壤盐渍化和沙化面积扩展; 气候变暖对粮食作物生长有抑制作用, 因为干旱半干旱地区温度升高使冬小麦生长发育加快, 生长期缩短, 作物可利用的有效水资源相对减少, 致使作物的总干重和穗重减少, 从而影响产量 The trend of warming and drying is intensified, especially in North China and Southwest China. The area of soil salinization and desertification in north China is expanding. Climate warming has an inhibitory effect on the growth of food crops because of the reduction of total dry matter weight and ear weight of crops, which was due to the acceleration of the growth and development of winter wheat, shortening of growth period and reduction of available water resources for crops caused by the rising temperature in arid and semi-arid areas	●冬季变暖会促进区域设施农业的发展 Winter warming will promote the development of regional facility agriculture
	●林果业优势产区改变, 如陕北黄土高原苹果种植、攀枝花热带水果种植等, 成为新的大型优质水果生产基地, 促进当地经济发展 The advantageous areas of forestry and fruit industry have changed, such as apple planting in the Loess Plateau of Northern Shaanxi and tropical fruit planting in Panzhihua, which have become new large-scale production bases for high-quality fruit and promoted local economic development	●由于气候变暖引起的冰雪融化、蒸腾增加, 土壤水分减少, 绿洲农业区域缩小 Due to the melting of snow and ice caused by climate warming, the plant transpiration increases, the soil moisture decreases, and the agricultural area of the oasis shrinks
	●气候变暖改变海洋渔业资源分布, 冷水鱼分布范围缩小, 高纬度地区海洋捕捞渔业增加、热带地区减少 Climate warming changes the distribution of marine fishery resources. Distribution area of cold water fish decreases, while the marine capture fishery increases in high latitudes and decreases in tropical areas	
	●海水酸化影响海洋生态, 对珊瑚、贝壳类海洋生物影响尤甚; 海水酸化影响海鲜食物的品味 Ocean acidification affects marine ecology, especially for coral and shellfish, as well as the taste of seafood	

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续表 2

影响层次 Effect level	已经发生的气候变化导致的农业脆弱性 Agricultural vulnerability induced by changed climate	未来气候风险 Future climate risk
农业气象灾害加剧 Intensified agro-meteorological disasters	●农业气象灾害整体表现为多发、并发趋势, 其中旱涝灾害交替出现、高温与干旱叠加, 发生频率增加, 危害程度加重, 影响范围扩大, 因灾损失增加 The overall performance of agro-meteorological disasters is characterized by frequent and concurrent trends, e.g., alternating droughts and floods and high temperature and drought superposition. The frequency of disasters increases with increased harm degree, influenced area expands more widely, and losses due to disasters also increases	●气候本身波动性加大, 极端天气气候事件频发、强度增大, 高温、低温、干旱、洪涝及各种复合灾害的危害范围扩大 The climate volatility will increase, extreme weather and climate events become more frequent and intense, and the harm scope of high temperature, low temperature, drought, flood and various combined disasters will expand
	●高温热害加剧, 作物高温逼熟、早稻热害、果蔬灼伤等灾害频发, 谷物秕谷率增加; 农业低温灾害频繁发生, 有些低温灾害甚至加重, 长江中下游地区冬春低温寡照危害加剧 The high temperature and heat damage are aggravated. For example, disasters like heat-forced maturity, heat damage of early rice, burn of fruits and vegetables, are more and more frequently occurs, and the rate of blighted grain increases. Agricultural low-temperature disasters also frequently occur, and some low-temperature disasters are even aggravated. In the middle and lower reaches of the Yangtze River, the damage of low temperature in winter and spring is aggravated	●水资源分布更加不均匀, 抵消由于生长季延长带来的增产潜力, 局地的水资源短缺形势会更加严峻 The distribution of water resources will be more uneven, which will offset the potential for increased production due to the lengthening of the growing season, and the situation of local water shortages will be more severe
	●北方干旱与西南干旱常态化与扩大化、长江流域伏旱频繁发生, 种植结构整体向旱生化演替; 洪涝灾害成灾面积逐年增加, 水土流失更为严重, 尤其是在西北地区; 台风强度和危害加大, 路径北移 (例如 2020 年东北遭受台风三连击) Drought in north China and Southwest China became normal and extended. In addition, drought occurred frequently in the Yangtze River basin. The planting structure express the trend of xerophilization. The area affected by flood disaster is increasing year by year, and soil erosion is more serious, especially in Northwest China. Intensity and damage of typhoon increased, and the path moved northward. For example, Northeast China suffered three consecutive typhoons in 2020	●虽然气候的整体趋势是变暖的, 但在局地地区很可能发生极端的、历史上罕见的低温, 其造成的危害和损失可能更大 Although the overall trend of the climate is warming, extreme and historically rare low temperatures are likely to occur in local areas, which may cause greater harm and damage
	●草原气候灾害加剧, 寒潮、雪灾、暖干化和沙化加剧 Climatic disasters in the grassland have intensified, such as cold wave, snow disaster, warming and drying climate and desertification	●对于农业动物体来讲, 由于气候本身波动的增加, 冷应激与热应激的风险都会加大, 养殖业面临更大的挑战, 对畜舍、鱼塘等设施提出了更高的要求 For agricultural animals, due to the increase of climate fluctuations, the risk of cold stress and heat stress will increase. The aquaculture industry is facing greater challenges, putting forward higher requirements for facilities such as livestock houses and fish ponds
	●气温的波动增加林果花期冻害的风险; 季节性干旱影响林果的萌芽开花, 出现落果现象, 影响林果产量和品质; 降水增多不利于果树开花授粉, 导致落花、落果、裂果增多, 水果减产 The fluctuation of temperature increases the risk of frost damage during flowering period of fruits. Seasonal drought affects the germination and flowering of forest fruit, which causes the phenomenon of fruit drop then affects the yield and quality of fruits. The increase of precipitation is not conducive to the flowering and pollination of fruit trees, resulting in the increase of falling flowers, falling fruits and cracked fruits. Therefore, fruit production decreases	●设施农业与工厂化养殖可以有效降低农业生物体对于气候灾害的暴露程度, 但一旦遭遇不可抗拒的极端气候灾害, 损失更加惨重 Facility agriculture and factory farming can effectively reduce the exposure of agricultural organisms to climate disasters. However, once they encounter irresistible extreme climate disasters, the losses are even much greater
	●高温及其引发的赤潮等海洋生物灾害给海水养殖造成巨大经济损失; 台风强度加剧严重损坏海水养殖设施, 如鱼塘漫顶、塘基崩塌、网箱损毁等; 暴雨造成海水池塘淹没、养殖网箱冲毁 Marine biological disasters, e.g., high temperature and its induced red tide, cause huge economic losses from mariculture. The intensification of typhoon seriously damaged the mariculture facilities, such as the overtopping of fish ponds, collapse of pond foundations and damage of cages. Heavy rain causes the inundation of seawater ponds and destruction of aquaculture cages	
生态后果 Ecological consequences	●气候变暖加快土壤有机质的微生物分解, 导致土壤有机质含量下降, 土壤微生物菌群改变, 引起土壤污染、土壤盐碱化以及土壤板结, 耕地质量下降 Climate warming accelerates the microbial decomposition of soil organic matter, resulting in the decrease of soil organic matter content and the change of soil microbial flora. These might cause soil pollution, salinization and compaction, which finally lower down the soil quality	●气候变化改变有害生物适生地分布, 由于天敌分布的改变往往滞后于病虫害的扩张, 在新发区域病虫害治理难度更大 Climate change alters the distribution of pests suitable habitats, while the change in the distribution of natural enemies often lags behind the expansion of pests and diseases, then it is more difficult to control pests and diseases in newly occurring areas

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续表 2

影响层次 Effect level	已经发生的气候变化导致的农业脆弱性 Agricultural vulnerability induced by changed climate	未来气候风险 Future climate risk
	●气候变暖、极端天气气候事件增加, 改变了病虫害的生境, 导致病虫害的种群结构、适生区域、发生时段、发生与流行程度等变化, 病虫害加剧 Climate warming and increase of extreme weather and climate events have changed the habitats of diseases and pests, resulting in changes in the population structure, suitable areas, occurrence time, occurrence and prevalence of diseases and pests, these might lead to more pest and disease incidents	●气候变暖导致病虫害加重与农药施用量增加, 对天敌也造成杀伤, 并使有害生物的耐药性加强, 从而形成恶性循环, 多种因素的叠加导致农业生物多样性保护面临更大的挑战 Climate warming causes the intensification of pests and diseases occurrence and then more pesticides application, which may kill natural enemies and strengthen the pesticide-tolerance of harmful organism, thus forming a vicious circle, and the superposition of multiple factors leads to greater challenges for the protection of agricultural biodiversity
	●暖冬使病虫越冬北界北移、海拔上限高度升高; 暖春使病虫害危害期提前、扩展速度加快、发生程度加重; 作物害虫繁殖代数增加, 病虫害爆发时间周期缩短, 病虫发育历期缩短、危害期延长, 害虫种群增长力、繁殖世代数增加; 危害面积扩大, 向高纬度、高海拔地区延伸, 损失巨大 Warm winter caused the north boundary of overwintering diseases and insects to move northward and the upper altitude-ward. Warm spring makes the damage period of diseases and pests advance, the expansion speed is accelerated, and the occurrence degree is aggravated. The multiplication algebra of crop pests increases, the outbreak time period and the development period of pests are shortened, and the harm period is prolonged. The growth power of pest population and the number of breeding generations increase. The damage area is expanded, which extends to high latitude and high altitude areas, resulting in huge loss	●气候变暖会使动物疫病与寄生虫病向高纬度与高海拔蔓延, 发生范围扩大, 外来生物入侵以及杂草的危害风险更大 Climate warming will make animal diseases and parasitic diseases spread to high latitudes and high altitudes causing the expansion of occurrence scope. The risk of alien biological invasion and weeds will be greater
	●气候变化会导致物种丰富度下降、生物多样性减少, 进而导致作物种质资源减少, 作物生产的适应性降低; 气候变化可能会诱发遗传变异, 威胁种质资源的安全与稳定 Climate change leads to the decrease of species richness and biodiversity, resulting in the decrease of crop germplasm resources and crop production adaptability. Climate change may induce genetic variation and threaten the security and stability of germplasm resources	●目前气候变化对土壤微生物结构和群落的影响机理很不清晰, 很可能酝酿着粮食产量和品质的巨大隐患, 乃至于局地的农业生态系统在气候变化超出其能承受的阈值时导致整体粮食生产系统的崩溃, 对当地的农业生产造成灾难性的后果 At present, the impact mechanism of climate change on soil microbial structure and community is very unclear, which is likely to breed huge hidden dangers in food yield and quality, and even lead to the collapse of the whole food production system when the local agro-ecosystem exceeds the threshold of its tolerance for climate change, resulting in disastrous consequences for local agricultural production
	●生态系统的退化影响其服务功能, 传粉昆虫种类和数量减少, 导致授粉服务功能减弱; 生态系统防治病虫害功能减弱, 农业病虫害加剧, 甚至导致部分农业生态系统的崩溃; 加大农业源温室气体排放, 农业气象灾害加剧导致生态系统固碳释氧和气候调节功能减弱; 局地气候调节功能受损, 导致水源涵养、净化功能降低; 增加土壤流失的风险, 引起农业土壤养分流失和盐碱化, 导致土壤保持等功能减弱 The degradation of ecosystem affects its service function, such as the species and quantity of pollinating decreasing and pollination service function weakening. The function of prevention and control of pests and diseases of ecosystem is weakened with intensified pests and diseases incidents even causing the collapse of some agricultural ecosystems. The increase of greenhouse gas emissions from agricultural sources and the intensification of agro-meteorological disasters lead to the weakening of ecosystem functions of carbon sequestration and oxygen release and climate regulation. The damage of local climate regulation service function leads to the reduction of water conservation and purification function. The increases of soil erosion lead to agricultural soil nutrient losses and salinization, resulting in weakened soil conservation and other functions	●海平面上升会使沿海地区面临更严重的海岸侵蚀、咸潮入侵、海岸带湿地退化等问题; 海水暖化酸化、珊瑚礁白化、赤潮等海洋生物灾害导致海洋渔业面临更大的风险 Sea level rise will make coastal areas face more serious coastal erosion, salt tide intrusion, coastal wetland degradation and other problems. Marine biological disasters such as ocean warming and acidification, coral reef bleaching, and red tide lead to greater risks for marine fisheries
	●草地暖干化导致生物量减少、草地物种多样性减少。动物疫病蔓延范围扩大, 局部地区爆发。以上改变对牲畜繁殖、生长发育、健康等造成很大的影响 The warming and drying climate of grassland results in the decrease of biomass and species diversity of grassland. Animal diseases spread more widely and broke out in some areas. Theses changes show a great impact on livestock reproduction, growth and development, health and so on	
	●水温上升影响养殖水体水质, 容易产生缺氧泛塘; 养殖鱼虾免疫力下降, 产量下降 The rise of water temperature affects the quality of aquaculture water, which is easy to produce anoxic flooding. The immunity of farmed fish and shrimp decreased, and the yield decreased	

续表 2

影响层次 Effect level	已经发生的气候变化导致的农业脆弱性 Agricultural vulnerability induced by changed climate	未来气候风险 Future climate risk
	●草原病虫鼠害加剧, 害草比例增大, 草原火灾频发, 杂草入侵, 草地生态供给功能下降, 草原畜牧业整体萎缩 The damage of grassland diseases, pests and mice increases, the proportion of harmful grass increases, grassland fires occur frequently, weeds invades, grassland ecological supply service function declines, and grassland animal husbandry shrank ●水温升高、海洋酸化等问题严重威胁到珊瑚礁的生存, 影响海洋生物资源的数量和品质, 改变渔业资源, 进而影响海洋捕捞业的产值。长江、黄河、珠海口富营养化、赤潮和水母的爆发等, 导致产量和品质下降 Problems such as rising water temperature and ocean acidification seriously threaten the survival of coral reefs, affect the quantity and quality of marine biological resources, alter fishery resources, and then affect the output value of marine fishing industry. Eutrophication of the Yangtze River, Yellow River and Zhuhai Estuary, outbreak of red tide and jellyfish, etc., led to the decline of yield and quality	
经济社会后果 Social-economic consequences	●极端气候事件导致粮食产量波动性加大; 主要经济鱼种和渔获量降低 Extreme weather/climate events lead to increased volatility of grain production. Major economic fish species and catches decreased ●CO_2 浓度升高导致农产品蛋白质含量下降, 改变农作物营养成分, 影响品质, 出现“隐形饥饿”问题 The increase of CO_2 concentration leads to the decrease of protein content of agricultural products, changes the nutritional composition of crops, affects the quality of crops, and causes “hidden hunger” ●气候变化加快食物变质, 如气候变暖导致食物 (尤其是玉米) 黄曲霉素含量增加; 长期阴雨导致作物穗上发芽, 海水酸化影响海鲜食物的味道, 气候变暖影响水果的糖酸比, 口感变差 Climate change accelerates food deterioration, such as increasing aflatoxin content in food (especially corn) due to climate warming. Long-term raining causes crops to sprout on the ears, ocean acidification affects the taste of seafood food, climate warming affects the sugar-acid ratio of fruits, and the taste becomes worse ●极端天气气候事件导致农田和养殖设施的破坏; 气候变化导致农业景观的破坏和农业景观丰富度降低等, 影响农村旅游业的发展; 传统非物质文化遗产的丧失等 Extreme weather and climate events result in the destruction of farmland and farming facilities. Climate change leads to the destruction of agricultural landscape and the reduction of agricultural landscape richness, which affects the development of rural tourism, and results in the losses of traditional intangible cultural heritage ●气候变化改变放牧模式 Climate change alters the grazing patterns ●气候变化通过对病原菌传播的影响, 也将对食品的生产、运输、销售和储藏全过程构成污染威胁, 影响食品的生产和安全, 增加人类传染病流行的风险 Climate change poses pollution threats to all aspects of food processing, transportation, storage and marketing via its impact on the transmission of pathogenic bacteria, and affects food supply and security, which increases the risk of human infectious disease epidemics ●高温、强降水、海平面上升、强风暴等极端天气气候事件危及公路、铁路、机场跑道、港口等交通设施的安全, 影响粮食运输过程, 导致运输成本增加 Extreme weather and climate events, such as high temperatures, heavy rainfall, sea level rise, and strong storms, threaten the safety of transportation facilities, such as highways, railways, airport runways, and ports, and affects the grain transportation, which increases transportation costs ●气候变化影响人们的饮食习惯, 高热量食物摄入减少, 低热量食物和冷饮需求增大 Climate change is affecting people’s dining habits, reducing the intake of high-calorie foods and increasing the demand for low-calorie foods and cold drinks ●气候变化引起农产品优势区的转移, 导致国内和全球农产品贸易格局的改变 Climate change causes the shift of the advantageous areas of agricultural products, leading to the changes of domestic and global agricultural trade pattern	●随着气候变化加剧, CO_2 浓度持续升高, 气候变暖不断加剧, 食物品质问题日益突显 With the intensification of climate change, CO_2 concentration continues to rise, climate warming continues to intensify, and food quality problems become increasingly prominent ●极端气候事件的持续加剧, 粮食系统的基础设施安全风险不断加大 As extreme climate events continue to be intensified, the security risks of the infrastructure of food systems are increasing ●国际粮食贸易与价格波动愈加不稳定 International food trade and price fluctuation are becoming more volatile

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热带北扩, 两熟制、三熟制种植北界北移等, 以及西藏河谷农业的发展、南方冬季蔬菜的种植等。气候变化导致热量、水分资源的改变和病虫害发生规律的改变, 作物与品种的适宜区随之发生变化, 引起作物布局、品种布局与种植模式的调整; 气候变暖使作物的种植期延长, 作物的适宜种植区向高纬度、高海拔地区扩展, 加之冬季变暖有利于冬季作物安全越冬和开发冬季农业; 在降水减少、气候暖干化的地区, 促使种植结构由耗水作物向耐旱作物的演替。利用热量资源增加的条件生产优质农产品, 如攀枝花咖啡、宁夏压砂瓜、陕西洛川苹果、黑龙江大米等, 是农业发展的机遇。

但气候变化对农业生产的不利影响远远大于有利影响。气候变化导致农业生态环境退化、农业气象和生物灾害日益加剧等。气候变暖加速土壤有机质分解和养分流失、北方冬季冻土变浅; 极端降水事件增加加剧水土流失; 气候暖干化导致农业水资源减少, 北方地区和西南地区尤为明显; 草地土壤含水量减少, 植被退化, 优良牧草比例降低, 局部草地沙化、盐碱化加重; 旱涝急转加剧西南地区的石漠化; 农作物适生地的改变, 加剧的病虫害导致农药的过量使用, 与人类活动一起造成农业生物多样性的减少, 农业生态系统生态服务功能降低。气候变化加剧高温热害, 作物高温逼熟, 谷物的秕谷率增加, 早稻热害、果树蔬菜灼伤等灾害频繁发生, 长江流域夏季尤为明显; 由于气候变暖导致气候本身的波动性加大, 加之变暖条件下作物抗寒能力下降, 农业低温灾害仍频繁发生, 在某些时候甚至造成严重的低温灾害; 气候暖干化导致北方干旱与西南干旱常态化, 气候波动加剧长江流域伏旱频繁发生, 局地干旱灾害造成作物颗粒无收; 洪涝灾害成灾面积逐年增加, 台风强度加大, 南方洪涝灾害加剧, 北方局地洪涝灾害加剧, 西北融雪性洪水灾害频繁发生; 气候变化导致旱涝灾害交替出现, 发生频率增加、危害程度加重、影响范围扩大, 农业气象灾害多发、并发, 高温干旱叠加、低温寡照并存, 导致特大农业气象灾害频发。气候变化导致农业病虫害发生产生新特征。气候变暖导致作物病虫越冬死亡率降低、冬后有效病虫源基数显著增加; 部分虫害的首现期、迁飞期及高发期提前; 气候变暖导致病虫害种类和世代数增加、为害期延长、为害范围扩大, 尤其是向北扩展蔓延趋势明显; 动物疫病向高纬度高海拔地区蔓延; 某些次要和新发生病虫害为害加重, 有些次要病虫害上升为主要病虫害, 新发病虫害由于缺乏防控措施为害更加迅猛、更加严重, 如台风活动增强导致稻飞虱和稻纵卷叶螟等水稻“两迁”害虫蔓延至长江沿线地区; 气候变暖与人类活动加剧外来物种入侵与人兽共患病的危害等[11]。

气候变化对食物品质的影响也需要引起高度重视。如果只考虑 CO_2 浓度升高, 理论上讲有利于增强植物的光合速率和提高水分利用效率, 但碳氮比的增加会使农产品的蛋白质含量下降, 改变食物营养成分, 影响农产品的品质, 出现“隐形饥饿”问题; 高温逼熟导致水稻精米率下降、蛋白质含量降低。气候变化加快病菌和病毒的传播, 影响食品加工、运输、储藏、销售过程的各个环节, 食物变质的可能性加大。从源头生产上说, 作物病虫害加剧和土壤有机质下降影响作物品质, 例如气候变暖导致食物(尤其是玉米) 黄曲霉素含量增加, 长期阴雨导致作物穗上发芽, 海水酸化影响海鲜食物的味道, 气候变暖影响水果的糖酸比, 口感变差。

未来农业生产面临的气候变化风险是多方面的, 既有气候变化本身带来的直接风险, 又有气候变化导致的生态风险, 还有由于不合理的人类活动带来的管理上的风险。

不断强化的气候胁迫, 给农业生产带来直接的生产风险。气候本身波动性加大, 极端天气气候事件增多增强, 高温、低温、干旱、洪涝以及各种复合灾害的危害范围扩大。水资源分布更加不均匀, 抵消由于生长季延长带来的增产潜力, 局地的水资源形势会更加严峻。需要强调的是, 虽然气候的整体趋势是变暖的, 但在局地地区很可能发生极端的、历史上罕见的低温, 其造成的危害和损失可能更大。对于农业动物体来讲, 由于气候本身波动的增加, 冷应激与热应激的风险都会加大, 养殖业面临更大的挑战, 对畜舍、鱼塘等设施提出了更高的要求。设施农业与工厂化养殖可以有效降低农业生物体对于气候灾害的暴露程度, 但一旦遭遇不可抗拒的极端气候灾害, 损失更加惨重。

气候变化改变农业生态系统结构和功能, 生态风险愈益错综复杂。气候变化导致有害生物适生地分布的改变, 由于天敌分布的改变往往滞后于病虫害的扩张, 新发区域病虫害治理难度更大。气候变暖导致病虫害加重与农药施用量增加, 对天敌也造成杀伤, 并使有害生物的耐药性加强, 从而形成恶性循环, 多种因素的叠加导致农业生物多样性保护面临更大的挑战。气候变暖会使动物疫病与寄生虫病将向高纬度与高海拔蔓延, 外来生物入侵以及杂草

的危害风险更大。目前气候变化对土壤微生物结构和群落的影响机理很不清晰, 很可能酝酿着粮食产量和品质的巨大隐患, 乃至于局地的农业生态系统在气候变化超出其能承受的阈值时导致整体粮食生产系统的崩溃, 对当地的农业生产造成灾难性的后果。海平面上升会使沿海地区面临更严重的海岸侵蚀、咸潮入侵、海岸带湿地退化等问题; 海水暖化酸化、珊瑚礁白化、赤潮等海洋生物灾害导致海洋渔业面临更大的风险。

不合理的人类活动加剧管理风险。在当前的农业适应实践中, 存在盲目适应的问题, "过度适应"使作物面临更大的生产风险, 尤其是过度引种晚熟品种、喜温作物种植界限过度北移、过早播种和移栽等导致低温灾害在气候变暖背景下反而加剧; 作物单一种植、过度依赖化学手段防治病虫害, 导致农业生物多样性下降, 农业生产系统的抗逆能力下降。作物水资源管理粗放, 非工程节水措施、生态节水措施不足, 干旱风险形势严峻。农业保险制度还很不完善, 一旦巨灾发生, 农民的生计和健康面临很大的不确定性。

3　已采取的适应措施总结回顾

从表 2 的总结可以看出, 气候变化对中国的农业生产产生了广泛而深刻的影响, 农业适应气候变化势在必行。农业是通过采取人为调控措施适应气候变化最密集的领域, 中国在保障粮食安全方面具有丰富的适应气候变化的实践经验。本节同样基于文献 [1-4,6,9-12] 总结已经采取的农业适应气候变化措施 (表 3)。

除表 3 总结的适应措施外, 中国也发布了一系列的政策文件, 如《中共中央 国务院关于深入推进农业供给侧结构性改革 加快培育农业农村发展新动能的若干意见》(中国政府网 https://www.gov.cn)、《中共中央 国务院关于实施乡村振兴战略的意见》(中国政府网 https://www.gov.cn)、《中共中央 国务院关于坚持农业农村优先发展做好"三农"工作的若干意见》(中国政府网 https://www.gov.cn)、《中共中央 国务院关于抓好"三农"领域重点工作确保如期实现全面小康的意见》(中国政府网 https://www.gov.cn)、《中共中央 国务院印发〈乡村振兴战略规划 (2018—2022 年)〉》(中国政府网 https://www.gov.cn)、《全国农业现代化规划 (2016—2020 年)》(中国政府网 https://www.gov.cn)、《"十三五"农业农村科技创新专项规划》(中华人民共和国科学技术部 https://www.most.gov.cn)、《全国农业可持续发展规划 (2015—2030 年)》(中国政府网 https://www.gov.cn)、《中共中央 国务院关于落实发展新理念加快农业现代化 实现全面小康目标的若干意见》(中国政府网 https://www.gov.cn) 和《农业农村部等 6 部门联合印发〈"十四五"全国农业绿色发展规划〉》(中国政府网 https://www.gov.cn) 等, 加强适应气候变化工作。早期的适应事项主要是常规工作的加强, 其后不断扩展至由于气候变化产生的额外事项, 适应气候变化的指向性逐渐增强。

从 2016 年起, "智慧气象"写入中央一号文件, 而"智慧气象"是"气候智慧型农业"的基础。其后的政策文件明确强调了农业生物多样性的重要性; 倡导利用气候变暖的有利机遇, 发展特色农产品, 加大农业保障水平; 倡导通过农业适应气候变化, 推动高品质农产品、绿色低碳农产品的生产, 推动气候智慧型农业的发展, 促进农产品价值链的提升。而在农业部等 8 部委发布的《全国农业可持续发展规划 (2015—2030 年)》政策文件里, 强调农业生态、高新技术的重要性, 同时提出建设多个类型的农业可持续发展试验示范区。在农业农村部等 6 部委联合发布的《"十四五"全国农业绿色发展规划》中, 明确指出: 农业主要依靠资源消耗的粗放经营方式仍未根本改变, 绿色优质农产品供给还不足; 提出的目标是到 2025 年, 农业绿色发展全面推进, 资源利用水平明显提高, 农业生态系统明显改善; 到 2035 年, 农业绿色发展取得显著成效, 农村生态环境根本好转, 绿色生产生活方式广泛形成, 农业生产与资源环境承载力基本匹配, 生产生活生态相协调的农业发展格局基本建立。这都可以作为农业适应气候变化规划与行动实施的重要抓手。

4　农业适应气候变化面临的挑战

总体上说, 气候变化增加农业系统的脆弱性, 未来气候风险亦愈益加剧, 适应气候变化面临愈加严峻的挑战。目前对于农业适应气候变化, 从科学认知、到公众意识提升、再到政策法规制订, 以及基础设施建设布局等各个层次方面, 都还存在很大的差距, 各个方面的工作都还需要加强。提升科学认知, 是农业适应气候变化的源头, 目前我们的科学认知还远不能满足适应行动实践的需要。比如对于以变暖为主要特征的气候变化趋势, 农作物生育期的延长、种植界限整体北移, 具有增产的潜力, 对于保障粮食安全有积极的意义, 但作物品种过度北扩则

表 3　中国农业已经采取的适应气候变化措施

Table 3　Adopted agricultural adaptation measures to climate change in China

适应层次 Adaptation level	适应现状 Adaptation status
气候变暖 Climate warming	●“自主适应”案例实践。华北“两晚”技术的推广、冬麦北移、东北水稻和玉米扩种及品种调整、热带作物种植北扩、提升复种指数 “Autonomous adaptation” cases. The promotion of “two-later” technology in North China Plain, the northward migration of winter wheat, the expansion and variety adjustment of rice and corn in Northeast China, the northward expansion of tropical crop planting, and the improvement of multiple cropping index ●改进作物栽培和养殖管理。为适应气候变化带来的物候改变, 北方水稻春播期和南方早稻播栽期普遍提前, 冬小麦播种期普遍推迟; 为减轻气候波动和低温灾害的影响, 大面积推广地膜覆盖; 为应对干旱威胁普遍推广节水技术和保护性耕作; 为减轻水温升高引发的泛塘死鱼, 淡水养殖场普遍使用增氧机; 为遏制气候暖干化导致的草原退化, 大力推行退牧还草和围栏轮牧, 提倡季节性放牧及与农区合作易地育肥, 夏秋打草储存冬春舍饲, 近年来草地植被明显恢复 Improve crop cultivation and breeding management. In order to adapt to the phenological alteration due to climate change, the spring sowing date of rice in north China and the transplanting date of early rice in south China are generally advanced, and the winter wheat planting date is generally delayed. In order to reduce the impact of climate fluctuation and low temperature disaster, plastic film covering is applied in a large area. Universal use of water-saving techniques and conservation farming are in response to the threat of drought. In order to reduce the dead fish caused by rising water temperature, fresh water farms have widely promoted aerators. In order to curb grassland degradation caused by warm and dry climate, the restoring grazing to grassland, fence-rotation grazing, seasonal grazing, cooperation with agricultural areas for land transfer and fattening, and forage harvesting in summer and autumn for storage in winter and spring are promoted. In recent years, grassland vegetation has recovered significantly ●种植结构调整。调整作物品种布局与种植制度, 规避灾害风险和充分利用气候资源。包括: 调整种植制度, 提高复种指数, 多熟种植向高纬度高海拔地区扩展。调整作物布局, 随着气候变暖, 北方冬小麦和华南热带作物种植北界向北扩展。调整品种布局, 为充分利用气候变暖所增加的热量资源, 春播作物普遍改用生育期更长品种, 加强抗逆品种选育和推广, 在暖干化地区推广耐旱作物品种, 灾后种植特早熟品种; 由于病虫害加剧, 抗虫棉、脱毒种薯种苗的推广种植等 Adjustment of planting structure. Adjust crop variety layout and planting system to avoid disaster risk and make full use of climate resources, including adjusting planting system, e.g., increasing multiple cropping index, expanding multi-cropping to high latitude and high altitude area; adjusting crop layout, e.g., expansion of the northern boundary of winter wheat and tropical crops in south China northward with the warming of climate; adjusting variety layout. To make full use of the heat resources increased by climate warming, spring crops are generally shifted to varieties with longer growth period, and the selection and promotion of stress-resistant varieties are strengthened. Drought-tolerant varieties are promoted in warm and dry areas, and exceptionally early varieties are planted after disasters. Due to the aggravation of pests and diseases, insect-resistant cotton and virus-free potato seedlings are popularized and widely planted.
农业气象灾害加剧 Enhanced agro-meteorological disasters	●加强农业气象灾害防御工作。针对中国北方大部和西南部分地区气候暖干化与干旱加重, “十一五”以来对大中型灌区进行了续建配套与节水改造; 针对南方和北方部分地区洪涝加剧, 进行了大中型和重点小型病险水库的除险加固; 逐步建立健全了突发事件应急体制与机制, 农业减灾重点从抗灾救灾转移到风险防范, 编制了一系列应急预案, 加强了救灾物资储备, 调整了作物布局。针对气候变化带来的农业生产不稳定性增加, 积极开展农业灾害保险试点工作; 加强了粮食与饲草的储备; 干旱缺水地区大力推广节水灌溉与农艺技术 Strengthen prevention of agro-meteorological disasters. In view of the warming and drying climate and the worsening drought in most parts of north and southwest China, the large and medium-sized irrigation areas have been rebuilt and water-saving reconstruction has been carried out since the 11th Five-Year Plan. In view of the intensification of flooding in some parts of south and north China, large and medium-sized reservoirs and key small reservoirs in danger have been strengthened. China has gradually established and improved the emergency response system and mechanism, shifted the focus of agricultural disaster reduction from disaster relief to risk prevention, formulated a series of emergency plans, strengthened the reserve of disaster relief materials, and adjusted the cropping distribution. In response to the increasing instability of agricultural production caused by climate change, the pilot work on agricultural disaster insurance are actively carried out. Reserves of grain and forage are strengthened. Water-saving irrigation and agronomic techniques are vigorously promoted in arid and water-scarce areas
生态后果 Ecological consequences	●改善农业生态, 治理水土流失。营造水土保持林, 实施“三北”防护林生态工程, 修建各种小型水利水保工程, 工程措施与生物措施相结合, 提高植被覆盖率, 治理水土流失, 减少土壤侵蚀 Improve agricultural ecology and control soil erosion. There are some measures, e.g., construction of soil and water conservation forests, implementation of the “Three North” shelterbelt ecological project, construction of a variety of small water conservancy and water conservation projects, combination of engineering measures and biological measures, to increase vegetation coverage, control and reduce soil erosion ●加强农业生物灾害防控。防治有害生物入侵, 推广了高效低毒农药和生物防治技术, 推广抗虫棉品种、寄生蜂防治玉米螟和松毛虫等生物防治技术 Strengthen prevention and control of agricultural biological disasters. To prevent and control the invasion of harmful organisms, China has popularized high-efficiency and low-toxicity pesticides and biological control technologies, and popularized insect-resistant cotton varieties, parasitic wasps to control corn borer and pine caterpillar ●提出“一控两减三基本”的目标。“一控”是要控制农业用水的总量, 划定总量的红线和利用系数率的红线; “两减”是把化肥、农药的施用总量减下来; “三基本”则是针对畜禽污染处理问题、地膜回收问题、秸秆焚烧的问题采取措施, 通过资源化利用的办法从根本解决这些问题, 制定一系列配套的政策与实施措施 Put forward the goal of “one control, two minus, three basics”. “One control” is to control the total amount of agricultural water, draw the red lines of the total amount and the utilization coefficient rate. “Two minus” is to reduce the total amount of fertilizer and pesticide application. “Three basics” is to take measures for the treatment of livestock and poultry pollution, the recycling of plastic film, and the burning of straw, and to solve these problems fundamentally by means of resource utilization, and formulate a series of supporting policies and implementation measures

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续表 3

适应层次 Adaptation level	适应现状 Adaptation status
经济社会后果 Social-economic consequences	●开展“气候智慧型农业”作物生产的实践。在安徽怀远县、河南叶县建立示范区, 围绕水稻、小麦、玉米三大生产系统, 开展作物生产减排增碳的关键技术集成与示范、配套政策的创新与应用、公众知识的拓展与提升等活动, 提高化肥、农药、灌溉水等投入品的利用效率和农机作业效率, 减少作物系统碳排放, 增加农田土壤碳储量。通过技术示范与应用、政策创新以及新知识普及, 建立气候智慧型作物生产体系, 增强项目区作物生产对气候变化的适应能力, 推动中国农业生产的节能减排, 为世界作物生产应对气候变化提供成功经验和典范 Crop production practice of “climate-smart agriculture”. Demonstration zones in Huaiyuan County, Anhui Province, and Ye County, Henan Province have been established, which focused on the three major production systems of rice, wheat and corn, and carry out activities such as integration and demonstration of key technologies for crop production, GHGs emission reduction and carbon-sink increase, innovation and application of supporting policies, expansion and improvement of public knowledge, improvement of the utilization efficiency of inputs (e.g., fertilizers, pesticides and irrigation water), agricultural machinery operation efficiency, reduction of crop system carbon emissions and increment of soil carbon storage in farmland. Through technology demonstration and application, policy innovation and popularization of new knowledge, a climate-smart crop production system are establishing to enhance the adaptive capacity of crop production in the project area to climate change, promote energy conservation and GHGs emission reduction in China’s agricultural production, and provide successful experience and model for the world’s crop production to cope with climate change ●完善粮食储备体系, 增强宏观调控能力。按照国际粮食安全警戒线, 中国粮食储备数量应为 8500 万~9000 万 t, 而中国粮食储备数量的安全警戒线应高于联合国粮农组织确定的 17%~18% 的标准线, 以相当于全年粮食总消费量的 25%~30% 为宜。中国粮食年总消费量大体为 5 亿 t, 按此标准计算, 国家粮食储备量应保持在 1.25 亿~1.50 亿 t, 而中国目前的粮食储备在 1.50 亿~2.00 亿 t。中国经受住了 2008 年汶川大地震和南方雪灾等多次特大自然灾害的考验, 就是因为充足的粮食储备在粮食流通和宏观调控中发挥了巨大作用 Improve the grain reserve system and strengthen macro-control capacity. According to the international food security warning line, the China’s grain reserves should be between 85 million and 90 million tons, and the safety warning line of China’s grain reserves should be higher than the FAO standard line of 17%~18%, which is equivalent to 25%~30% of the total annual domestic grain consumption. China’s total annual grain consumption is roughly 500 million tons, and according to this standard, the national grain reserves should be maintained at 125~150 million tons. However, China’s current grain reserves are between 150−200 million tons. China has withstood the test of several major natural disasters, such as the Wenchuan Earthquake in 2008 and the snowstorm in southern China, because sufficient grain reserves have played a huge role in grain circulation and macro-control ●加强市场宏观调控, 确保粮食流通的良性循环。健全粮食市场体系, 加强粮食物流体系建设, 加快法规、制度体系建设, 合理调整储备粮品种结构, 拓宽轮换粮源市场, 增强和改善粮食宏观调控手段, 提高粮食宏观调控能力, 发挥储备体系宏观调控载体作用, 保证市场供给, 确保粮食市场和价格基本稳定, 抑制通货膨胀, 确保粮食流通的良性循环 Strengthen macro-control of the market to ensure a virtuous cycle of grain circulation. Improve the grain market system, strengthen the grain logistics system, speed up the development of laws and regulations and systems, rationally adjust the structure of grain reserve varieties, expand the rotation of grain source markets, strengthen and improve the means of grain macro-control, increase the capacity for grain macro-control, give play to the role of the reserve system as a carrier for macro-control, and ensure market supply, ensure the basic stability of grain markets and prices, curb inflation, and ensure a virtuous cycle of grain circulation ●阻断粮食能源化利用, 保证粮食供求平衡。由于能源紧缺, 中国必须大力发展生物能源, 但应把重点放在发展以木薯、甘薯、甜高粱等为原料的燃料乙醇技术, 以及以小桐子、黄连木、油桐、棉籽等油料作物为原料的生物柴油生产技术, 并积极发展以纤维素等物质为原料的生物液体燃料技术, 阻断粮食能源化之路。这是保证粮食供求平衡, 保障粮食安全的一个有效对策手段 Block the energy-oriented use of food, and ensure the balance of food supply and demand. Due to energy shortage, China must vigorously develop bio-energy focusing on the development of fuel ethanol technology with cassava, sweet potato and sweet sorghum as raw materials, as well as biodiesel production technology with oil crops such as jatropha, Chinese pistacia, oilseed and cottonseed as raw materials, and actively develop bio-liquid fuel technology with cellulose as raw materials. This is an effective countermeasure to ensure the balance of food supply and demand and ensure food security ●保证原粮及粮油食品卫生安全。健全法律法规, 完善粮油食品市场管理和监督体系, 不仅要在粮油食品生产、加工过程中全面、严格、高质量地实施质量管理体系, 而且在储藏、运输及经营过程也要注意存在的或潜在的危害因素 Ensure the hygiene and safety of raw grain, cereal & oil food. Improve laws and regulations, and the market management and supervision system of cereal & oil food. Not only establish quality management system in the production and processing process of cereal & oil food, but also pay attention to the existing or potential harmful factors in the storage, transportation and business process ●提高粮油食品安全科技水平, 优先研究可靠、快速、精确的粮油食品安全检测技术, 并积极推行食品安全的控制技术。大力加强粮油食品生产企业 ISO9001、ISO9002、ISO14000、HACCP 体系和 GMP、无公害食品、绿色食品、有机食品的认证。积极开展新技术、新工艺、新材料加工食品的安全性评价技术的研究, 确保粮油食品安全。大力开展原粮及粮油食品的卫生检验, 不断制订完善的卫生标准 Improve the scientific and technological support to the cereal & oil food safety, prioritize the research on reliable, fast, and accurate cereal & oil food safety testing technology, and actively promote food safety control technology. Vigorously strengthen the cereal & oil food production enterprises ISO9001, ISO9002, ISO14000, HACCP systems and GMP, pollution-free food, green food, organic food certification. Actively carry out the research on the safety evaluation methodology of new technology and new material processed food to ensure the safety of cereal & oil food. Vigorously carry out the hygiene inspection of raw grain and cereal & oil food, and constantly formulate perfect hygiene standards ●推进供给侧结构性改革。提高农产品在国际市场的竞争力, 发挥适度规模经营的引领作用, 扩大种地面积, 降低粮食生产成本, 提高农民收入和种粮积极性 Advance supply-side structural reform. Raise the competitiveness of agricultural products in the international market, play the leading role of appropriately scaled farming, expand the area of farmland, reduce the cost of grain production, and increase farmers’ income and motivation to grow grain ●提高应对粮食安全威胁的能力。一是政府加大对三农的支持力度, 加强财政、金融的支持; 二是在保证小麦、稻谷及玉米生产充分的情况下, 适当调整粮食生产结构, 增加大豆等产品的生产; 三是加强农业、粮食生产领域的科技投入, 不断提高粮食生产力 Improve ability to cope with the threats onto the food security. Firstly, the government increases support for agriculture, rural areas and farmers, and strengthen fiscal and financial support. Secondly, properly adjust the grain production structure and increase the production of soybean and other products under the condition of ensuring adequate production of wheat, rice and corn. Thirdly, enhance the scientific and technological inputs in agriculture and grain production, and continuously improve grain productivity

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加剧冷害的发生, 效果则适得其反。气候变化引起极端天气气候事件加剧, 导致农业气象灾害加剧, 以及农业生态整体的退化, 加大农业系统的脆弱性, 危害粮食安全, 需要有针对性地增强农业的气候韧性, 这就需要对农业气候韧性增大到什么程度合理具有清晰的科学认识, 过度的适应浪费资源, 适应不足则不能有效减轻气候变化带来的损失, 从 2022 年长江全流域的高温干旱、2021 年河南农作物洪灾情况来看, 我国农业的气候韧性还需要大力加强。

气候胁迫不断加大。在气候变暖的趋势下, 气候的波动性越来越大, 极端天气气候事件的发生频率增多、强度和危害范围扩大, 农业生产面临着不断加剧的高温、低温、干旱、洪涝等气候胁迫的直接冲击。这就需要选育抗逆性强的高产优质抗逆作物、畜禽水产和林果花草良种, 匹配相应的研发、生产等的基础设施和技术储备, 但目前对农业生物体响应气候变化的机理缺乏足够的认识, 对农业生产面临的气候危险性的科学认知和技术储备远远不足。

农业系统对于气候变化的脆弱性不断加大。农业单一种植导致的生物多样性减少, 加之不合理的人类活动, 导致农业生态系统的功能减弱, 使农业生产体系本身直接暴露于气候胁迫之下, 直接经受更多的气候冲击。再者, 气候变暖导致的温暖环境下作物生长缺乏抗寒锻炼、农业可用水资源的减少、过度适应变暖气候的越界种植、追求高产的作物育种导致的作物抗逆性能下降, 以及作物病虫害与动物疫病加剧、渔业养殖设施与海洋捕捞业面临极端天气气候事件的安全威胁加大等诸多因素叠加导致农业生产对于气候的变化越来越敏感。

粮食安全社会保障体系还很不完善。从农业产业全链条安全的角度看, 气候变化加快食物变质、加剧病菌和病毒的传播, CO_2 浓度升高降低农产品蛋白质含量, 改变食物营养成分; 极端天气气候事件危及交通设施的安全, 影响粮食运输过程, 导致运输成本增加。现代化、全球化背景下, 农业的产业链不断加长, 粮食系统的安全保障面临越来越大的不确定性。

适应能力薄弱是制约农业适应气候变化行动有效开展的瓶颈。从基础设施的角度来讲, 农业基础设施还很不完善, 存在"适应赤字"现象, 在气候加速变化的背景下, 农业基础设施更需完善加强。从适应气候变化的管理能力来讲, 各种法规还很不完善, 与适应气候变化的需求还很不匹配, 适应气候变化的资源优化调配体制机制建设任重道远, 科技支撑能力亟需大力加强。

5 农业适应气候变化关键科学问题

对 IPCC 发布的气候变化评估报告[8,13-17]、典型发达国家 [German Strategy for Adaptation to Climate Change; National Climate Resilience and Adaptation Strategy-DAWE; Climate Change: Second National Adaptation Programme (2018 to 2023)] 和发展中国家 [National Climate Change Action Plan 2011—2028 (Climate Change Commission), 2020; Climate Change Adaptation in Peru: The Local Experiences (Soluciones Prácticas), 2010; National Climate Change Strategy (United Republic of Tanzania Vice President's Office), 2012; New Challenges for Food Security in Vietnam (Vietnam Academy of Agricultural Sciences), 2020] 发布的适应气候变化战略或规划、联合国粮农组织[18-19]和全球适应委员会[20] 等机构发布的报告进行系统回顾可以看出, 气候变暖引起的级联效应, 使气候变化的影响充满了不确定性。因此, 必须切实转变观念, 采取综合的、超常规的、变革性的适应行动增强农业气候韧性, 实现从"自主适应"向"计划适应"的转变、从"增量适应"向"转型适应"的转变、从防灾减灾到气候灾害风险管理的转变、从单一适应技术到适应技术体系集成的转变。倡导农业适应和减缓的协同, 建立整个社会的粮食安全保障体系, 建立基于气象指数的农业保险体系, 加大金融机制创新, 加强农业新技术的研发与应用推广。发展气候智慧型农业 (CSA), 大力倡导保护农业与粮食系统的生物多样性, 充分发挥农业生态系统的服务功能, 是农业可持续发展的必由之路。农业适应气候变化行动的实施, 需要大力加强科技创新, 切实提升农业适应气候变化能力。

扩展气候变化农业影响评估研究领域。科学认识的不足是我们采取适应行动的一个关键瓶颈。目前对气候变化对农业的影响评估主要集中在粮食产量方面, 对于气候变化对作物品质和"生产—加工—运输—储存—销售"全链条影响的认识远远不足。而即使对于粮食生产, 针对种植业、草地畜牧业的气候变化影响评估研究较多, 对养殖畜牧业、林果业、渔业、海洋捕捞业等的影响评估研究相对较少。

科学辨识农业之于气候变化的脆弱性和风险。依据 IPCC 报告[17], 未来气候风险是气候危险性、暴露度和脆弱性的函数。气候危险性是和 GHGs 排放路径紧密相关的, 高排放的路径气候危险性高; 无序

发展加大农业系统的暴露度; 不合理的结构导致脆弱性增加, 而适应能力对减轻气候脆弱性至关重要。这些都是构成气候风险的因素。当前对农业气候风险笼统描述得多, 缺乏对各个分量进行细致拆分的定量表述。适应的目的就是降低农业气候风险、增强农业可持续发展的气候韧性。只有对气候风险有了深刻细致的科学认识, 才能有的放矢地有效开展适应行动增强农业气候韧性。优化国土空间规划, 尤其是充分发挥生态系统的气候调节功能, 可以改善局地气候, 降低气候危险性; 遮阴措施减轻对作物的高温灼伤、养殖棚舍建设可以降低畜禽对高低温的暴露度; 调整农业种植结构、增加生物多样性, 改善农业生态系统的结构与功能以降低农业生产对于气候变化的脆弱性, 有大量的科学问题需要深入研究。

揭示农业适应气候变化的科学机理。气候条件的改变, 农业系统的各个部分之间的相互作用关系亦随之改变, 需要揭示农业生物体自适应机理与人为调控机理, 这是农业适应气候变化的关键核心科学问题。

构建农业适应气候变化技术体系。农业适应气候变化, 最终要通过技术措施实现。在揭示农业适应气候变化科学机理的基础上, 需要进一步发展农业适应气候变化技术体系的原理和框架, 以及构建适应技术体系的方法。农业适应技术体系可以是"草根"技术的集成创新, 在中国长期的农业生产实践中, 积累了大量的适应技术, 对这些技术措施进行系统梳理, 可以凝练出经济可行的"草根"农业适应技术体系; 农业适应技术体系也可以是高新技术的创新, 如在浙江省松阳县茶园开展的集合物联网 (IoT) 和大数据构建的自动喷灌系统试验[19], 可以达到节水 50%、节肥 40%、减少农药用量 35%、节电 50%、节约人工 95% 的效果, 使试点茶园免受 2017 年高温干旱、2018 年霜冻的危害, 具有良好的适应和减缓协同效果, 显示农业适应技术创新具有巨大的潜力。

根据所要解决的适应问题, 可以构建多种形式的技术体系。按照适应的方式, 可以构建增量适应技术体系或转型适应技术体系; 按照不同的气候风险, 可以构建抗旱节水的技术体系、病虫害防治技术体系等; 按照不同的适应逻辑层次, 可以构建农业气候资源高效利用技术体系、减灾技术体系等。各个区域面临不同的气候风险和适应挑战, 其适应技术体系亦具有鲜明的区域特色。

加强农业适应气候变化的决策能力研究。适应气候变化不同于减缓, 一地一部门的适应很可能损害其他地方和部门的利益, 需要在全局整体统筹农业协调适应气候变化的行动。目前适应行动规划制订的一个最大问题是适应目标不清晰, 气候变化的影响评估与要采取的适应措施之间没有很好地对应。要解决这样的"两张皮"问题, 需要科学合理地评估农业气候风险, 在风险评估基础上确定明晰的适应目标。基于当前的适应水平达到确定的适应目标, 可以有多种多样的实现路径, 这就存在适应路径的选择问题、存在"增量适应"或"转型适应"方式的选择问题。

加强农业适应行动实施的保障能力研究。要根据气候变化导致的农业气象灾害、生物灾害发生的新特征, 有针对性地加强监测预警, 有针对性地加强农业基础设施建设, 完善农业保险体制, 建立抗逆品质基因库和救灾种子库, 培养高光效、耐高温、抗寒抗旱、耐盐碱的作物品种, 加强农民适应技术培训等。从管理层面上说, 需要完善农业适应气候变化的政策法规标准修订, 发展农业适应行动实施的监测评估指标体系。开展适应气候变化的技术示范研究, 建立农业适应气候变化技术示范基地, 系统总结气候智慧型农业实践的经验和理论方法, 支撑气候智慧型农业在全国范围的推广。

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