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# 生态学报

（SHENGTAI XUEBAO）

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## 目　　次

**城乡与社会生态**



**研究简报**



**学术信息与动态**



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**封面图说**:云南松树冠——云南松为松科松属裸子植物,多生长在海拔 1000—3500m 的高山,喜光、耐干旱、耐瘠薄,适应酸性的红壤、黄壤,在其他树种不能生长的贫瘠石砾地或冲刷严重的荒山坡分布,易于天然更新。主要分布于四川西南部、云南、西藏东南部、贵州西部、广西西部,常形成大面积纯林,尤以云南分布最广,故有云南松之称。云南松树高可达 30m,胸径达 1m,树皮呈灰褐色,叶通常 3 针一束,鲜有两针,球果圆锥状卵圆形,种子近卵圆形或倒卵形。树干通直,木质轻软细密,是优质造纸、人造板原料,富含松脂是云南松的重要特点之一。

**彩图及图说提供**:陈建伟教授　北京林业大学　E-mail:cites.chenjw@163.com

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# 灾后生态恢复评价研究进展

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**摘要**:灾后生态恢复评价是恢复生态学重要研究方向之一,从 20 世纪 90 年代开始,随着研究手段和防灾减灾意识的提高逐渐成为研究的热点。灾害生态恢复评价以森林火灾、地震及地质灾害、旱灾、采矿及地面沉降、火山喷发、飓风 6 大灾害为主要研究领域,以不同时间序列生态系统演替、不同条件下受灾生态系统恢复效果差异性和相关性分析以及受灾生态系统生态恢复趋势预测为研究内容,针对退化生态系统的结构、功能、过程进行评估和鉴定。当前,灾害生态恢复评价采用的指标包括遥感和地面两大类,方法分为单因子对比法、综合指数法、模拟预测法、反推法。针对灾后生态恢复评价指标缺乏系统性、参照系过于单一性以及对灾区后续恢复指导性不强等问题,未来应在技术框架流程、指标体系分类归纳、生态恢复标准阈值制定、以及生态恢复评价应用等方面加强研究,以体现灾后生态恢复评价评估结果的科学性、客观性以及对生态系统管理的作用。

**关键词**:灾害;生态恢复; 研究进展

## Research advances and prospects of post-disaster ecological restoration assessment

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**Abstract**: Post-disaster ecological restoration assessment as one of the key research directions of restoration ecology assumes, with reference to specific goals and systems, the role of assessing and appraising the change of structure, function, quality, health and safety of damaged or degraded ecosystem during the restoration succession, after an interval of certain time following natural or induced disaster. It is inevitably the requirement for determining the degree of ecosystem restoration, testing the effect of restoration pattern and screening out the feasible ecological restoration project. Ever since the 90s of the last century, it has by no means halted at any occasions in enticing the attention more than ever from the research fellows, in parallel with the improvement of research methods and hiked public awareness of necessity of disaster prevention and mitigation. Post-disaster ecological restoration assessment is conducted mainly towards highly frequent disaster with severe ecological damage, covering six major types of disasters, namely forest fire, earthquake and geological disaster, drought, mining and ground subsidence, volcanic eruption and hurricane. Research content extends to three aspects, i.e. ecological succession under various time series, differentiation and correlation analysis on restoration effect of the affected ecosystems under various conditions and trend prediction of the ecological restoration of the affected ecosystems. Based on various indices of the reference systems, the assessment indices could be categorized as two parts: 1) the remote sensing indices based on pre-disaster reference systems, such as NDVI, vegetation coverage, leaf area index, land use type and landscape pattern indices, etc.; 2) ground indices based on unaffected reference systems or on restoration property, such as species composition, biomass, species richness, thickness of trees and shrubs, tree height and DBH, and soil

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indices in terms of soil moisture, pure soil composition, organic carbon and nutrient (N、P、Ca and K) content, etc. Presently there are four key assessment methods, which are single factor comparison method (comparison of time series between vegetation and soil factors), comprehensive index method (comparison of ecological safety, health and stability before and after disaster), simulation method (cellular automata model and Markov chain intended to simulate and predict dynamic changes of damaged ecosystem) and inverse method (assessment of the effect of disaster prevention and mitigation intended to reconstruct the ecological restoration condition). In wake of the problems like absence of systematic feature, overly unitary reference system and inefficacy in guiding the subsequent restoration of the disaster areas, prospective researches on technical framework process, classification and induction of index system, formulation of the ecological restoration standard threshold and application of ecological restoration assessment should be revved up for the good of showcasing the scientific and objective features of the assessment conclusions and of rendering the boost to the ecosystem management.

**Key Words**: disaster; ecological restoration; research advance

恢复生态学是20世纪80年代迅速发展起来的应用生态学学科，主要从事生态退化机理、退化生态系统修复技术与方法、模式及工程以及生态恢复评价等方面的研究,对指导生态系统建设,优化生态系统管理具有重要的理论和实践意义[1-2]。生态恢复评价是恢复生态学的重要研究范畴,它是掌握生态系统恢复程度,检验恢复模式成败,筛选科学合理生态修复工程的必然需求[3]。自然和人为灾害,如森林火灾、飓风、旱灾、地震及地质灾害、火山爆发、采矿、过度放牧等,会对生态系统产生破坏和干扰并使其退化,直接或间接的危机人类的生命财产安全,因此了解灾后生态系统恢复状况对于制定中长期生态修复措施及防灾减灾对策起到关键作用。随着研究手段和人们防灾减灾意识的提高,从20世纪90年代开始,灾后生态恢复评价逐渐成为生态恢复学研究的热点。本文从生态恢复评价的定义出发,归纳总结了灾后生态恢复评价的主要研究领域、研究内容、指标体系和评价方法,提出了灾后生态恢复评价的技术思路,指出了存在的问题和未来需解决的关键技术,为进一步凝练生态恢复学研究成果,促进灾后生态恢复评价理论的发展奠定基础。

## 1 生态恢复评价的内涵

生态恢复评价是指以特定目标和系统为参照,针对受损或退化生态系统在恢复演替过程中的结构[4-7]、功能[8]、质量[9-10]、健康[1]、安全[11-12]等变化进行评估和鉴定。生态恢复评价在发展历程中有三种说法,即效果评价[8,13-16]、效应评价[17-18]和效益评价[3,19-23],3种说法实质含义和研究内容是不一样的,但许多研究者并没有加以区分,在使用时较容易混淆。效果评价是指与既定目标或参照系统对比,生态系统组分、结构、格局的恢复状况。效应评价是指该生态系统的恢复对其它生态环境产生的有利或不利效应,如植被的恢复对水、大气、土壤、其它生物带来的影响。效益评价是指生态系统恢复后产生的社会价值、经济价值、生态价值,是生态恢复货币化的表现,如震后森林的恢复带来的林业经济效益以及生态服务价值的提高。效果评价强调生态系统结构的恢复,体现生态系统的完整性;效应评价强调生态系统功能的恢复,即生态系统能量流动、物质循环、信息传递功能的恢复,体现生态系统的平衡性和稳定性;效益评价体现生态系统服务功能的恢复,即为人类服务和改变社会经济环境能力的恢复,体现生态系统的外部性。

由于灾害具有突发性强、破坏性大、恢复周期长的特点,因此对于灾后生态恢复的研究优先考虑的是生态系统组分、结构、格局的变化,效果评价成为灾后生态恢复评价的主导。

## 2 灾后生态恢复评价研究进程

### 2.1 横向研究热点

从灾害发生来源可知,灾害分为气象灾害、地质灾害等自然灾害以及人为灾害,每种灾害对生态系统的影响和破坏程度不一样。以灾害名称、生态恢复、植被恢复等为关键词查阅了国内外较权威的文献数据库 CNKI 和 Science Direct,统计了研究灾后生

态恢复政策、技术、管理、评价的相关文献(表 1)从表 1 中可以看出灾后生态恢复评价主要围绕发生频率较高、对生态破坏较大的灾害展开,研究频次最高的属 6 大灾害,依次为森林火灾、采矿及地面沉降、地震及地质灾害、飓风灾害、旱灾、火山喷发。在森林火灾生态恢复评价方面,地中海沿岸国家由于特殊的地理环境成为研究的典型区域[24-30],此外美国、加拿大、中国、巴西、俄罗斯等森林面积较大的国家也是关注的热点地区[31-33]。在地震及地质灾害生态恢复评价研究方面,我国汶川地震灾区和台湾地区是研究的热点地区,特别是以林文赐为首的研究团队针对台湾集集地震发生后九九峰和九分二山地区进行了长期深入的研究,成为地震灾后生态恢复评价研究的典型代表[34-38]。旱灾生态修复主要在农业领域展开,重点研究农作物在干旱和恢复状况下生理生态响应[39-43],以及土壤动物种群的变化对农业生产的影响[44-45]。在采矿与地面沉降方面,主要针对矿山废弃地开展数十年、甚至上百年的植被恢复研究[46-50],因为矿山废弃地的植被恢复主要为裸岩的原生演替,需要数十年甚至更长的时间。火山喷发和飓风灾后生态修复研究的热点区域主要在美国和加拿大,火山喷发重点研究火山岩沉积区植被的演替[51],而飓风灾害重点研究灾后城市森林的恢复[52]。

**表 1　灾后生态恢复评价研究文献统计**

**Table 1　Literature statistics of post-disaster ecological restoration assessment**

| 灾害类型 Types of disaster | 关键词 Keywords | 文献库 Literature library: CNKI 文献总数 Total of literature | CNKI 恢复评价文献数 Number of restoration assessment literature | Sicencedirect 文献总数 Total of literature | Sicencedirect 恢复评价文献数 Number of restoration assessment literature | 恢复评价文献合计 Total of restoration assessment literature |
|---|---|---|---|---|---|---|
| 地震 Earthquake | 地震,植被恢复,生态恢复 | 31 | 7 | 11 | 3 | 10 |
| 泥石流 Debris flow | 泥石流,植被恢复,生态恢复 | 7 | 3 | 5 | 1 | 4 |
| 崩塌,滑坡 Collapse and landslide | 滑坡,崩塌,植被恢复,生态恢复,修复 | 3 | 3 | 22 | 10 | 13 |
| 火灾 Forest fire | 火灾,林火迹地,植被恢复,生态恢复 | 20 | 7 | 289 | 214 | 221 |
| 旱灾 Drought | 旱灾,恢复 | 21 | 6 | 9 | 5 | 11 |
| 采矿 Subsidence and sedimentation | 采矿废弃地,植被恢复,生态恢复 | 170 | 30 | 218 | 158 | 188 |
| 塌陷与沉降 | 塌陷沉降,植被恢复,生态恢复 | 15 | 0 | 5 | 1 | 1 |
| 火山爆发 Volcano eruption | 火山,植被恢复,生态恢复 | 0 | 0 | 20 | 7 | 7 |
| 飓风,台风 Hurricane, typhoon | 风灾,植被恢复,生态恢复 | 7 | 5 | 56 | 15 | 20 |
| 雪灾 Snow disaster | 雪灾,植被恢复,生态恢复 | 2 | 1 | 10 | 2 | 3 |
| 洪灾 Flood | 洪水,洪灾,植被恢复,生态恢复 | 2 | 2 | 16 | 4 | 6 |

## 2.2　纵向研究内容

当前,灾害生态恢复评价包含 3 个方面的研究内容。(1)不同时间序列受灾生态系统演替研究。这种时间序列少则一年,多则数十年甚至上百年,通过对比灾前、灾后和恢复期相关参数对比评估受灾生态系统的演变趋势。Messier 等研究了加拿沙龙白珠树生态系统,在火灾后 2、4、8a 地上和地下植被恢复情况,对比了植被生物量、叶面积指数、根状茎比例等参数[31]。Clemente 等使用不同时相的 ETM 和 TM 遥感数据,评估了 1993—2005 年 13a 里地中海

某地火灾后森林再生格局的的变化[25]。林文赐研究了集地震发生后 1a[34]、2a[35]、6a[36]、7a[37]、10a[38,53]九九峰和九分二山植被恢复的变化,对比的内容包括滑坡面积、植被覆盖度、土壤年平均侵蚀深度等指标。(2)不同条件下受灾生态系统的恢复效果的差异性和相关性分析。这些条件包括不同受灾程度、不同处理处置方式、不同的保护措施、不同的自然环境本底条件、是否有外来种的干扰等。Dodson 等研究了植被恢复与森林火灾燃烧程度之间的相关关系,研究表明当秸秆焚烧物覆盖不超过 40%时,植被恢复与焚烧物覆盖呈正比,而当秸秆焚烧物覆盖超过 70%时,秸秆焚烧物覆盖开始呈现负作用,但总体说来秸秆焚烧物加快了缓慢的自然恢复过程[33]。Ne′eman 等研究了植被恢复与森林火灾后不同处理方式的相关性,研究表明“维持森林火灾后现状、砍掉残树保留细枝、残树和细枝全移除”这 3 种措施对于受灾区的物种组成和植被覆盖度没有影响[30]。Wang 等研究了植被恢复与土壤侵蚀的相关性,研究表明在长期遭受侵蚀的区域,由于根的缺乏自然植被恢复非常缓慢,而在坡地上种植一些经过筛选的木本植物则可加速植被恢复[32]。Knapp、Scott、Partridge 等研究了废弃采矿区植被恢复与外来物种干扰的相关性,研究表明无论废弃矿山还是废弃耕地,受损生态系统很难恢复到初始状态,因为这些区域受外来物种干扰较为强烈,阻碍了本地种的自然修复过程[46-47,50]。Hmmyashi、Brown、Mengistu 等研究了生态恢复与封育保护的相关性,研究表明封育是促进干旱区退化生态系统恢复的最有效的方法之一[54-56]。(3)受灾生态系统生态恢复趋势预测,这种预测即包括时间的预测,也包括效果的预测。Lesschen 认为半干旱环境下泥灰地和钙质结砾岩撂荒地至少需要 40a 的时间才能通过自然恢复达到稳定阶段[57]。Rydgren 等预测了阿尔卑斯山废土堆未来 50a 的植被恢复演替趋势,线性演替规律表明至少还需要 35—48a 的时间才能使废土堆与周边环境融为一体[48]。Lebrija 等研究了热带干燥森林采伐迹地植被演替的路径、机制和趋势,他们认为在最初的 10a 里先锋林占据主导,在接下来的 40—45a 里,先锋林逐渐减少,而成熟林成为主导[58]。Dale 等研究了 1980 年圣海伦火山爆发后生态系统的自然演替过程,他还预测在火山岩沉积区可能要数十年才能达到 100%的植被覆盖,而生态系统的完全恢复可能要花 100a 甚至更多的时间[51]。

**2.3 灾后生态恢复评价指标**

2004 年,国际生态恢复协会提出了退化生态系统恢复的 9 大属性[59],即:(1)具有与参考地点类似的物种多样性和群落多样性;(2)具有本地种;(3)对于生态系统长期稳定起重要作用的功能群体的出现;(4)生态系统能够为种群繁殖提供生境的能力;(5)生态系统功能维持能力;(6)生态系统景观的整体性;(7)生态系统潜在威胁的消除;(8)生态系统对于自然干扰的恢复力;(9)生态系统自我支持能力,为生态系统恢复评价指标的选择提供了方向。国内许多专家学者认为生态恢复指标应该包括物种多样性指标、植被结构指标以及生态过程指标,生物多样性指标包括动植物物种丰富度、植被结构指标包括植被覆盖、密度、高度、枯枝落叶结构、生物量等,生态过程指标包括土壤氮含量、土壤有机质含量、土壤有机碳等等[3,14,18,60-61]。也有专家指出生态恢复评价指标不应过于繁琐,用指示物种的丰富性和多样性也可反应生态系统的恢复状况[62]。该文统计了国内外灾后生态恢复评价普遍采用过的指标(表 2),按照参照系统的不同指标可分为两大类,一是遥感指标,包括归一化植被指数(NDVI)、植被覆盖度、叶面积指数、土地利用类型、景观格局指数等;二是地面指标,包括植被指标,如物种组成、生物量、物种丰富度、乔灌密度、乔木高度、胸径等,也包括土壤指标,如土壤水分、纯土壤成分、有机碳、营养物质(N、P、Ca 和 K)含量。遥感指标具有多时相的特征,往往用于基于灾前参照系统的恢复评价,而地面指标需要即时的现场测量,往往用于基于未受灾参照系统或基于修复目标的恢复评价。不同的灾害类型以及不同的参考标准往往选择的具体指标不一样。

**2.4 评价思路与方法**

**2.4.1 评价方法**

灾后生态恢复评价方法主要有指标对比法、综合指数法、模拟预测法、反推法 4 种。

(1)指标对比法 首先选择参考标准,通过研究区与对照区植被、土壤因子的时间序列对比来评价研究区的恢复状况。如受损区与未受损区、保护区与未保护区、一种措施与另一种措施在物种组成、多样性、丰富度等方面的对比[54,63,66,69-71]。

表 2　灾后生态恢复评价指标

Table 2　Indicators of post-disaster ecological restoration assessment

| 灾害类型 Types of disaster | 参考文献 Resources | 指标 Indicators |
| --- | --- | --- |
| 采矿 | 李江锋等[13] | 植被覆盖率,固体废弃物占地率,地表扰动率,土壤侵蚀率,土地垦殖率,坡地比,土地可利用率 |
| Mining | 李娜等[63] | 植被指数,叶绿素含量,物种数量 |
| | 陈思思等[64] | 土壤侵蚀模数,土壤养分,景观格局 |
| | 钟爽[65] | 景观格局 |
| 森林火灾 | Leeuwen,et al[66] | MODIS-NDVI |
| Forest fire | 肖向明等[67] | 叶面积指数,植被指数 |
| | 曾馥平等[68] | 土壤有机质,全 N,全 P,全 K,生物量 |
| | Messier 等[31] | 生物量,叶面积指数,细根占总根的比例,根状茎比例等。 |
| | Clemente 等[25] | 生物多样性指数(NDVI 和香农辛普森指数) |
| | Dodson[33] | 植被覆盖,物种丰富度,树苗密度 |
| | Ne′eman[30] | 物种组成,覆盖度,高度,密度和生物量 |
| | Minchella[29] | 生物量 |
| 旱灾 | Peters[69] | NDVI |
| Drought | Hayashi[54] | 灌丛密度,树木高度 |
| | Malabuyoc[43] | 土壤湿度 |
| | Maraldo[45] | 土壤水势,土壤含水量,线蚓生物量,密度 |
| 洪灾 | 李伟[70] | 水生植物类型,多样性 |
| Flood | 张美文[71] | 鼠群落结构 |
| 地震 | 潘倩[72] | 土地利用 |
| Earthquake | 王梦君[73] | 群落结构,生物多样性,生物量 |
| | 林文賜[34-38] | 土地利用,NDVI 指数,平均侵蚀深度,土壤侵蚀模数,景观格局指数,土壤水分 |
| 滑坡 | Reddy[74] | 纯土壤成分,有机碳,和土壤营养物质(N,P,Ca 和 K),物种序列,以及植物生物量 |
| Collapse and landslide | Whenua[75] | 茶树高度增长率,茎占面积,土壤深度 |
| 风灾 | 许冬焱[76] | 物种类型,丰富度 |
| Wind disaster | 赵晓飞[77] | 生物多样性,草根盘结度,土壤持水量,土壤孔隙度 |
| | Burley[52] | 土壤品质,本地种比例 |
| 火山爆发 Volcano eruption | Dale[51] | 物种丰富度,植被覆盖 |

(2)综合指数法　以植被、土壤、地理等多种参数建立综合评价指标体系,采用层次分析、模糊评价法、灰色评价、压力-状态-响应模型、主成分分析法等方法计算灾前、灾后生态安全、健康、稳定性等综合指数,通过指数的变化反应灾后生态恢复程度的大小[13-14,61,78]。

(3)模拟预测法　该方法以多时相的土地利用、土地覆盖数据为基础,采用细胞自动机模型或马尔科夫链来模拟和预测受损生态系统的动态变化,预测未来演替的趋势[79]。

(4)反推法　通过评估防灾减灾的效果来反推生态的恢复状况。如滑坡稳定性的评估,反推植被恢复状况对于滑坡稳定性的影响[80]。河岸稳定性研究河滨森林植被恢复状况[81]。

### 2.4.2　技术思路

灾后生态恢复评价技术路线见图 1 所示,主要包括 7 大流程:①对灾害生态环境影响进行全面回顾,分析影响范围、程度,明确灾后生态恢复评估范围和侧重点。②选择灾后生态恢复评价参考标准。既可以选择灾前参照,也可以选择相同自然条件背景下参照系,也可以自定义理想中的恢复标准。③筛选生态恢复评价指标体系,指标必须能同时描述受灾生态系统和参照生态系统。④明确指标体系参数获取方法,通过遥感解译、地面样方调查、采样实验室分析获取所需要的数据。⑤建立生态恢复评估模型。从以上所归纳的生态恢复评价方法中筛选、整合,建立适用于灾区实际情况的生态恢复评估模型。⑥将参数导入评估模型获取灾前、灾后生态评估综合指数,通过划定生态恢复阈值,判断灾后生态

恢复程度。⑦根据恢复效果的好坏,制定灾区未来的生态恢复措施和发展战略,并提出灾区生态风险防治措施等。

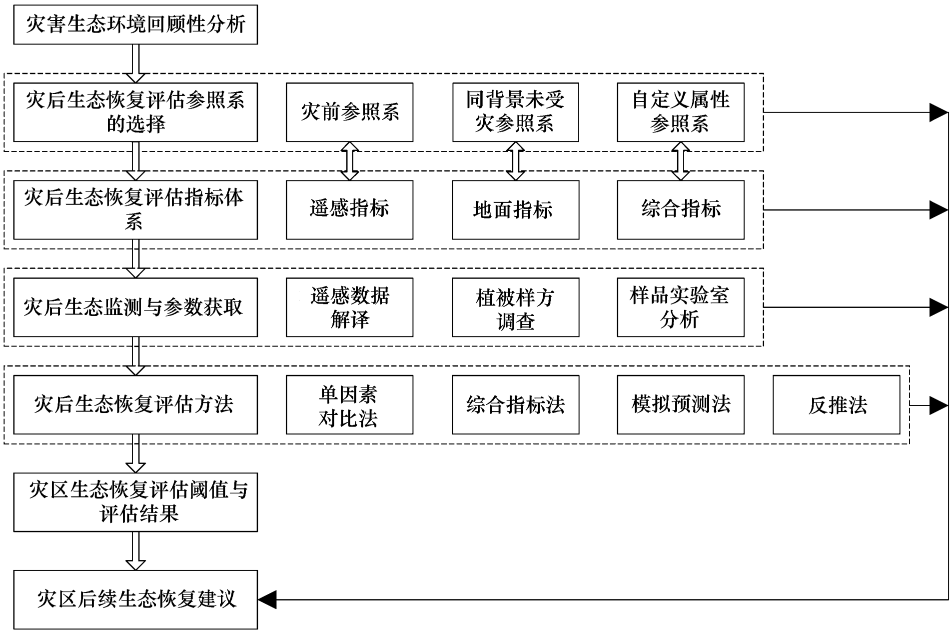


**图 1 灾后生态恢复评价技术流程**

**Fig.1 Technical process of post-disaster ecological restoration assessment**

## 3 灾后生态恢复评价研究展望

### 3.1 存在的问题

#### 3.1.1 灾后生态恢复效应评价指标针对性和系统性不高

国际生态恢复协会虽提出了退化生态系统恢复的 9 大属性,但对属性的定义比较模糊,导致生态恢复评价在指标选择上存在较大的差异性。如在属性 3 中,如何定义对生态系统长期稳定起重要作用的功能群体,在属性 8 中如何定义生态系统对干扰的恢复力,不同的研究者有不同的理解,在用指标去衡量这些定义时更是千差万别。同时可以看到,同类型的灾害以及同类型生态系统恢复的特征具有相似性,应建立统一的生态恢复评估体系,但目前这方面的研究工作还比较缺乏,导致灾后生态恢复评价的标准化和业务化程度不高。

#### 3.1.2 灾后生态恢复评价标准具有单一性,不能保证评价结果的准确性

目前灾后生态恢复参考标准有 3 种,一是灾前生态系统、二是相同背景下的未受灾生态系统、三是研究者自定义的生态恢复标准。从表 2 所采用的指标可以看出,目前研究者往往只选择单一标准来评价生态系统的恢复状况。单个恢复评价标准的建立有可能因为数据获取精度不高,或是因为地面调查的误差导致评价结果的错误。在这种情况下有必要建立多元的恢复评价标准,从不同的侧面反应生态恢复的总体效果,多个标准之间可以相互对比,相互支持,从而最大限度的提高评价结果的准确性。

#### 3.1.3 缺乏灾后生态系统恢复评价应用性研究

生态系统恢复评价的目的除了掌握灾后生态系统当前的演替情况外,还要为灾区后续恢复计划的制定、恢复措施的选择提供决策依据,也要为灾区生态安全提供预警。但目前大多数的生态恢复评价研究只是展示恢复结果,而没有对灾区后续发展提供指导和建议,这就大大降低了灾后生态恢复评价的科学意义。

### 3.2 生态恢复评价未来发展方向

针对灾后生态恢复研究存在的主要问题,该文认为应该加强以下几个方面的研究,促进灾后生态恢复评价理论、技术、方法的发展。

#### 3.2.1 建立灾后生态恢复评估框架体系

主要包括:(1)灾后生态恢复参照系筛选标准,明确一维参照系和多维参照系的适用情况。(2)在参照系的确定的前提下,确定生态恢复评价指标体

系的筛选原则,最大程度的体现参照系的基本属性。(3)生态恢复评估方法的选择原则。在不同的灾害类型下,哪种方法最大程度体现评估结果的客观性和准确性。

**3.2.2**　建立分门别类的灾后生态恢复评估指标体系

在分析森林火灾、地震及地质灾害、旱灾、飓风等灾害对生态环境影响基本特征的基础上,建立不同类型灾害、不同类型退化生态系统灾后生态恢复评估指标体系,进一步提高灾后生态恢复评估标准化程度。

**3.2.3**　建立灾后生态恢复标准阈值

标准阈值包括时间阈值和恢复阈值两个方面,即与参照系相比,在多大时间尺度下,评价指标达到什么程度表明退化生态系统正在恢复。阈值的确定是生态恢复评估的一大难点,但确是生态恢复评估的关键,应加强这方面的研究。

**3.2.4**　建立生态恢复评价应用和指导工作机制

加强不同恢复措施下,包括自然恢复、工程修复、人工造林、外来种引进等情况下生态恢复效果差异性研究,为受灾生态系统类型后续生态修复方案的选择提供理论支撑。同时加强灾后生态风险研究,为灾区进一步减灾、防灾建立预警机制。

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