

高原山区遥感植被制图研究综述^{* 1}

张志明, 张征凯, 郭银明, 陶国庆, 欧晓昆

(云南大学 生态学与地植物研究所, 云南 昆明 650091)

摘要: 植被制图是植被生态学研究的基础和重要内容之一. 在环境复杂、异质性高的高原山区, 由于诸多因素的影响给该区域的遥感植被制图带来很大的困难和挑战. 作者重点介绍在复杂山区环境中利用遥感技术进行植被制图的基本过程. 为了提高山区遥感植被图的精度, 建议注意以下几点: ①在提取训练样本阶段, 应将同一地物或者植被类型根据其不同的光谱特征分成不同亚类型进行选取训练样本; ②现有许多地形校正模型不能有效地提高遥感分类精度; ③分类器选择时, 建议选择人工智能神经网络分类法、决策树、基于专家知识分类法等先进的非参数分类器; 其次如果选择使用中低分辨率影像数据, 可以考虑使用亚像元或软分类法; 当使用高分辨率影像时, 选择基于对象分类法要优于基于像元分类法; ④结合辅助数据, 尤其是 DEM 数据能显著提高山区遥感植被或森林制图精度. 将来高级地形校正模型和分类算法需要进一步开发和发展. GIS 技术与遥感数据结合也是未来遥感植被制图技术发展的一个重要方向. 未来研究还需要将群落和植被生态学的理论和方法与遥感技术相结合来提高山区植被制图精度, 并促进遥感科学和空间植被生态学发展.

关键词: 植被制图; 高原山区; 遥感技术

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植被生态学研究是基础自然科学研究领域之一, 而植被制图是植被生态学研究的基础和重要内容之一. 植被图是农、林、牧、副、渔合理开发、利用和改造的重要依据之一, 在水土保持、沙漠治理、自然保护、绿化、轻工业原料和中草药基地的建立和规划设计, 以及国防建设等方面起着重要作用. 因此植被图无论在理论上还是实践上都具有重要意义^[1]. 植被图的精度高低和尺度大小直接影响下一步工作进程和质量.

在过去 20 多年中, 随着计算机和遥感技术发展, 植被制图技术发展迅速. 卫星遥感数据被广泛地应用于土地利用制图和植被制图及监测等方面^[2]. 应用遥感影像进行植被的分类制图, 尤其是大范围的植被制图, 是一种非常有效而节约大量人力物力的方法.

地处西南边陲的云南省 94 % 的区域为山地, 海拔分布范围从最低 70 m 到最高 6 740 m. 在环境

复杂、生境异质性高的高原山区, 不同植被类型的光谱分布特性与一般情况下的分布规律有较大的差别, 给那些仅依据光谱特性来进行影像分类的技术带来了困难^[3], 尤其是在高山峡谷区域, 植被分布受地形因子及其它环境因子影响较大^[4-7], 同时卫星影像受地形的影响会出现阴影效应 (shadow effect), 因此给该区域的遥感植被制图带来了很大的困难和挑战^[8-9].

有关介绍遥感影像分类制图的书籍和综述性文章很多^[10-14]. 本文主要关注在复杂山区环境中利用遥感技术进行植被制图的基本过程, 影响制图精度的主要因素, 以及影像处理和分类方法选择时需要注意哪些因素, 从而提高山区遥感影像分类精度, 完成高精度植被制图.

1 遥感植被制图过程

利用遥感影像进行植被制图是一个复杂的过

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作者简介: 张志明(1976 -), 男, 湖北人, 博士, 副教授, 主要从事景观植被和景观生态学及遥感和地理信息系统应用与开发研究工作. E - mail: zhiming_zhang76@hotmail.com

通信作者: 欧晓昆(1957 -), 男, 云南人, 博士, 教授, 主要从事植被生态学教学和研究工作. E - mail: xkou@ynu.edu

程,其主要步骤包括选定遥感数据、确定分类系统、提取训练样本、图像预处理、影像增强和转换、波段信息优选组合、选择合适的分类方法、分类后处理,及精度评估。

1.1 遥感数据的选择 遥感数据通常包括航片和卫星影像数据,这些数据具有空间、辐射、光谱和时间分辨率。了解不同传感器数据的优缺点对选择合适的遥感数据进行影像分类和植被制图是十分必要的。许多相关书籍详细介绍了不同传感器数据的特点^[2,10]。选择适当的传感器数据是成功进行影像分类制图的关键^[15-18]。选择遥感数据时需要考虑诸多因素,如研究者的要求、研究区的特点和尺度、各种影像数据的可获得性、经费和时间约束以及研究者的经验等^[19]。

影像空间分辨率和研究者的要求是影响遥感数据选择的最主要因素。研究者的要求决定了分类性质、研究区尺度,从而会影响遥感数据分辨率的选择。前期研究报道了尺度和分辨率对遥感数据分类的影响^[20]。通常对于小尺度研究区的分类,高分辨率的数据如 IKONOS、SPOT5 HRG 和 ALOS 数据是非常有用的。但对于区域尺度,中等空间分辨率数据如 Landsat TM/ETM+ 和 Terra ASTER 是使用最频繁的数据。对于大陆或全球尺度,低空间分辨率数据如 AVHRR、MODIS 和 SPOT 数据则更为合适。

大气状况是影响传感器数据选择的另一重要的因素。山区气候复杂,频繁的云经常成为获得高质量遥感影像的障碍。另外山区影像受地形影响产生阴影效应显著,有关阴影效应的影响和去除模型将在 1.3 节中详细说明。

此外,由于当前多源遥感数据较容易实现,影像分析中的遥感数据有了更多的选择。通常综合考虑不同传感器影像数据的特点有助于提高山区植被制图精度^[18]。

1.2 确定分类系统和选取训练样本 一个适当的分类系统和足够的训练样本是成功开展遥感影像分类的先决条件。Cingolani 等^[21]指出使用中等分辨率数据进行植被制图应注意 3 个问题:①根据遥感影像的空间分辨率确定植被分类等级;②根据选用的遥感数据确定的制图单元;③获取典型足够的训练样本。通常,分类系统的设计是根据研究者的需要,所选遥感数据的空间分辨率,与先前工作的兼容性,影像处理过程和分级算法的可行性及时间

约束等因素。这样的系统应当信息量大,详尽并且可分性好^[22-23]。一个分类等级系统往往需要考虑多种因素。

足够典型代表的训练样本对遥感影像分类至关重要^[23-26]。训练样本的采集通常是通过野外调查或者高分辨率的航空照片和卫星影像解译。不同的采集策略,如单个像元、多像元(seed)、多边形等,也会影响分类结果,尤其是对于高分辨率影像数据^[25]。

当研究区内的环境复杂且具异质性高时,训练样本的选择就变得很困难。如果使用中分辨率或低分辨率数据分类,由于可能有大量的混合像素,上述问题就会变得更复杂。对于复杂的山区环境,由于地形和阴影效应会造成同物异谱和异物同谱的现象,因此,前人研究表明在选取训练样本时,应将同一地物或者植被类型根据其不同的光谱特征分成不同亚类型,并分别选取训练样本,最后将分类结果进行合并,此操作能显著地提高分类精度^[10,27]。

此外,提取各个类型的典型波谱信息是成功进行影像分类的关键。前人发展多种提取波谱信息的方法:①图表分析(例如:柱状光谱图法、共同光谱平均向量绘图法、二维特征空间绘图和椭圆绘图);②统计方法(如:平均发散度、变形发散、Bhattacharyya 距离、Jeffreys - Matusita 距离)^[11,22]。这些方法其主要目的是测定不同类型的可分离性,进而纯化各个类型的训练样本。

1.3 遥感影像预处理 影像预处理一般包含坏线(bad lines)的检测和修复、几何校正和影像配准、辐射校正、大气校正和地形校正。如果使用不同的辅助数据,在其与遥感数据结合之前,需要对这些不同来源或格式的数据进行转换和质量评估。在分类过程中,首先要对不同来源的遥感数据进行精确的几何校正和影像配准^[22,28]。

如果在分类过程中使用了多时相或不同传感器数据,就必须进行大气校正^[29]。尤其是使用不同传感器数据,如综合使用 Landsat TM 和 SPOT 或 Landsat TM 和 Aster 数据进行分类时。现有的商业遥感软件(如 ENVI、ERDAS 和 IDRISI 等)都提供了多种大气和辐射校正方法。此外,对于研究区位于崎岖的山区时,影像分类之前通常需要进行地形校正^[30-31]。

如上所述山区影像的地形阴影效应明显,有必

要对地形校正进行说明. 在过去 30 年间, 人们发展了多种地形校正模型^[32-41]. 一个有效的地形校正模型应该能够减少或者去除地形效应和阴影, 乃至能提高山区植被制图精度. 但是有些学者研究表明现有的地形模型对提高山区遥感植被制图精度效果不明显, 并且不可能彻底去除深度阴影效应^[31, 33, 42]. 同时 Zhang 等^[31]建议在选取训练样本时将同一地物或者植被类型根据其不同的光谱特征分成不同亚类型进行选取训练样本能减少阴影效应和显著地提高影像分类精度.

1.4 影像增强和转换以及波段信息优选组合 影像分类制图中经常会用到许多潜在的影像信息, 如光谱特征、植被指数 (vegetation index)、纹理或关联信息 (contextual information)、影像转换, 以及多时段影像和多传感器影像及辅助数据. 由于山区植被分布复杂, 可分性差, 在分类过程中使用过多的冗余波段信息有时可能会影响分类精度^[43-44]. 所以在山区植被制图分类之前有必要进行波段组合优选. 其中为了降低遥感数据冗余信息最常用的方法有主成分分析 (principal component analysis, PCA)、最小噪音分数变换 (minimum noise fraction, MNF)、缨帽转换 (Tasseled Cap transformation, TASSCAP)、判别分析、边界特征抽取、非参数加权特征抽取、小波分析和混合光谱分析等^[25, 45-51]. 在山区遥感分类制图中, 有研究表明选择光谱波段比 (如 TM 影像的波段 4 与波段 3 的比值) 为附加变量能够减小阴影效应和提高分类精度^[19, 52].

1.5 选择适当的分类方法 选择合适的分类方法是成功进行遥感影像分类制图的关键之一. 遥感影像分类法通常可以被分为监督和非监督分类, 或者参数和非参数分类; 或者硬和软 (模糊的) 分类; 或者像元、亚像元和基于对象分类法 (object - based image classification)^[11-12]. Cihlar^[53]介绍了大区域土地覆盖制图现状及优先发展方向. Franklin 和 Wulder^[54]评估了中等分辨率遥感数据的土地覆盖分类法. 其中最大似然分类法 (maximum likelihood classification, MLC) 是最经典的参数监督分类法, 被广泛地应用于像元分类^[12, 55]. 由于该分类方法首先假设各类型样本数据符合高斯正态分布模型, 然后通过计算各个类型的概率来区分各个类型^[55], 然而许多类型的样本数据并非符合正态分布模型. 近年来, 人们发展了许多高级分类方法, 如人工智能神经网络 (artificial neural network,

ANN), 该分类法是一种非基于样本统计参数的监督分类法^[56-58]. 尤其是在开展山区遥感影像分类研究中, 许多类型样本数据并非遵循正态分布模型^[27]. 相对于 MLC 而言, ANN 方法已被证实能够显著地提高山区遥感影像分类精度^[31].

如上所述, 由于山区环境的高度异质性, 中高分辨率影像中混合像元是非常普遍现象. 亚像元分类法具有解决中低空间分辨率影像中混合像元影响问题, 并获得高精度分类结果的潜力^[59-60]. 许多前期研究已经表明亚像元分类能提高土地覆盖分类精度和面积估算^[61-65].

亚像元分类法通常采用模糊集合理论 (fuzzy - set theory)、光谱混合分析 (spectral mixture analysis)、MLC 和 ANN 软分类、Dempster - Shafer 理论等. 其中模糊集合理论^[66-69]和光谱混合分析^[70-72]是最常用的方法. 前人已经证明光谱混合分析法能够有效地提高影像分类精度以及植被覆盖率评估, 尤其是利用低分辨影像数据^[72-76].

随着卫星技术的高速发展, 近年来越来越多的高分辨率的影像数据得以应用, 如 Quikbird 和 IKONOS 等影像数据. 如果利用这些高分辨率的遥感影像数据进行山区植被制图, 同样由于山区的植被景观高度异质性会造成同一植被类型的光谱信息变异大, 传统基于像元分类法产生的结果破碎化程度高, 产生大量的“噪声”效应, 严重的影响分类结果精度. 然而自本世纪初得以发展起来的基于对象分类法 (object - based) 能很好地解决这一问题^[77-81].

总而言之, 由于遥感数据的空间分辨率, 数据来源, 以及分类系统和分类软件的不同等因素, 并且不同的分类方法有各自的优点, 所以在具体研究中选择哪种分类方法是一个很难回答的问题. 总体上当前有 3 种遥感影像分类算法: 基于像元算法、亚像元算法、基于域 (或称为基于对象) (per - field or object - based). 其中基于像元分类法还是最常用的方法. 然而如上所述, 当使用中低分辨率遥感数据进行植被制图时, 由于混合像元的影响, 选择亚像元分类法能取得更高的分类精度. 而当使用优质的高分辨率遥感数据时, 尽管混合像元减少了, 但由于植被或土地覆盖类型的光谱信息变异, 使用基于像元分类法很可能会降低分类精度. 而基于对象分类法比较适合高分辨率遥感影像分类. 当使用多源数据时 (如光谱特征组合、纹理和关联信息、

辅助数据),先进的分类器(如神经网络、决策树、专家知识分类)可能更适合用于处理这些复杂的多源数据,所以近年来这些分类方法获得了遥感领域的持续关注^[11,58]。

1.6 分类后处理 传统的基于像元分类法产生的分类图中经常会有“盐和胡椒”效应(‘salt and pepper’ effects),即分类图中经常有1个或者几个像元组成的孤立类型。所以分类后的植被或者土地覆盖图通常需要利用优势滤波器(majority filter)来平滑(smooth)消除这些“盐和胡椒”效应^[10]。

此外大部分影像分类是基于遥感光谱特征进行的,但是对于山地环境,由于其生物物理环境的复杂性,不同植被类型光谱信息界限不清。所以传统上对于山区遥感影像解译的结果(植被图、森林图、土地覆盖图等)通常需要根据一些专家知识并结合相关辅助数据进行修正。例如滇西北梅里雪山地区的植被分布与海拔、坡度和坡向相关性很强,云南松林分布海拔不高于2 800 m,而冷杉林分布海拔一般为3 200~4 200 m^[82]。植被的空间分布规律可以用于分类后植被图修正。前人研究表明,分类后处理是提高分类质量的重要措施^[83-86]。

1.7 精度检验 遥感影像植被制图的最后一个重要环节就是精度评估,精度评估是评价影像最终解译结果和植被制图质量,以及定量比较评估不同分类方法的重要步骤。Congalton 和 Green^[87]已经系统地介绍了分类结果精度评估的原理和应用。同时 Foody^[88]也综述了遥感数据分类结果的精度评估方法以及分析影响精度评估有关问题。

在评估分类精度之前,需要了解引起误差的来源^[89-90]。一般除了分类本身产生的误差,还有其他误差来源,如遥感数据几何校正中产生空间位置误差,以及训练或测试样本数量不足和质量不高等等这些都会影响分类精度评估。此外选择合适的取样方法是准确评估分类精度的一个关键步骤^[91]。取样方法主要包括取样单位(点或多边形)、取样设计和样本大小^[92]。通常取样方式有随机取样、分层取样、系统取样、二次取样和集群取样。此外对于样本大小,一般建议用于检验每种植被或者土地覆盖类型的样本数不少于50个^[10]。前人已经对有关取样技术做了详细描述^[87,93]。

当前,混淆矩阵法(error matrix)是应用最广泛的精度评估方法^[87-88,94]。混淆矩阵能非常有效地评估遥感分类图的精度,并且能够给出各个分类类

型的错分误差(commission errors)和漏分误差(omission errors)。错分误差是指其它类型被错误地分成某一类型,而漏分误差是指某一类型被错误地分成其它类型。此外,混淆矩阵法能计算出遥感制图的总体精度(overall accuracy)、生产者精度(producer's accuracy)、用户精度(user's accuracy)。Congalton 和 Green^[87]系统地介绍了精度评估的基本概念和一些高级的精度评估方法,如模糊逻辑和多层评估法,以及进行遥感分类精度评估的基本原则和应用。

混淆矩阵能计算 Kappa 系数,Kappa 系数是测定混淆矩阵总体一致性的重要指标。同时 Kappa 系数也是分析单一误差矩阵和比较多个混淆矩阵差异的有效方法^[91,95-96]。此外,基于归一化混淆矩阵精度评估法比传统的混淆矩阵法能更好地展示精度分析结果^[91,97-98]。

由于混淆矩阵法仅适用于“硬”分类,并且该方法首先是假设分类图的各个类别是完全排斥独立,每个像元是属于一个单一类别。然而对于低分辨率影像的混合像元而言,这个假设通常不成立,因此该方法不能使用于评估“软”分类结果。至此,许多新的评估方法得以发展,如条件熵(conditional entropy)和交互信息(mutual information)^[99-100]、模糊集(Fuzzy-set)^[101-102]、相似信息对称指数(symmetric index of information closeness)^[103]、Renyi 广义熵函数^[104],以及 Morisita 指数^[105]等。尽管如此,由于评估软分类(或者模糊分类)的关键问题是难以获取参考信息,因此发展一种适合评估模糊分类结果的方法还需要更多深入研究。

2 利用辅助数据提高山区遥感植被制图精度

前人研究已经证明结合辅助数据,如地形、土壤、道路和人口资料等,能提高遥感影像分类精度^[11,106]。尤其在山区,将遥感数据与地形辅助信息结合对提高土地覆盖和植被分类精度有显著作用^[52,77,107-108]。由于山区植被空间分布格局受地形影响显著^[108-113],因此数字高程模型(digital elevation model, DEM)是其最常用的辅助数据。通常有以下几种方式将 DEM 数据与遥感数据结合起来提高山区遥感分类精度:①与地形校正模型结合减少山区地形效应^[32-41];②DEM 作为一个额外波段与遥感数据结合起来提高森林植被制图精度^[8,77,114];③利

用决策树分类法与专家知识结合来提高山区植被制图精度^[115-118];④将植被分布与海拔关系与分类类型优先比率(prior probability)结合来提高分类精度^[3,19,116,119-121]。

如上所述,山区植被空间分布格局受地形影响显著。研究植被空间分布格局与其影响因子之间关系是植被生态学研究的核心内容之一^[122-123]。植被和群落生态学家主要关注植物群落和植被与环境因子(包括地形、土壤、气候等等)的关系,而遥感学家们主要关注光谱反应与地表特征的关系,相反忽略植被与环境因子之间关系。利用遥感来进行植被(尤其是群落层次)制图时通常会受到不同植被(或群落)类型的光谱相似性限制^[8,124-125]。因此当前需要将植被生态学的理论和方法与遥感技术结合起来进而提高大尺度山区植被制图及相关研究^[126-127]。

除此之外,由于高分辨遥感数据应用越来越广,为我们进行山区群落层次上的植被制图提供机遇和挑战^[128]。遥感影像的纹理特征也被广泛开发,并被应用于影像分类中^[81,129-132]。利用遥感数据的时相特征(不同季节)是提高山区遥感植被制图精度的另一有效措施^[116,133-135]。

3 总结和展望

过去几十年中,遥感技术有了长足的发展,并且在山区植被制图、变化检测、森林防火、病虫害预测和防范中得以广泛应用。获得高精度的山区植被图或者土地覆盖图是进行相关研究的基础。

利用遥感影像进行山区植被制图是一个非常复杂的过程,需要考虑的因素很多,如空间尺度大小、时间尺度、分类系统类型、遥感数据特点、地形阴影效应、分类方法等等。如上所述,进行遥感植被制图的主要步骤包括选定遥感数据、提取训练样本、图像预处理、影像波段信息优选组合、选择合适的分类方法、分类后处理,以及精度评估。其中重点注意以下几点:①在提取训练样本阶段,要将同一地物或者植被类型根据其不同的光谱特征分成不同亚类型,并分别进行选取训练样本;②现有许多地形校正模型不能有效地提高遥感分类精度,所以在山区植被制图过程中笔者建议不要花过多的精力和时间利用地形校正模型去消除阴影效应;③在选择分类方法时需要考虑遥感数据的光谱特征、空间和时间分辨率等因素。首先在山区影像分类制图

中,由于分类样本并非遵循正态分布模型,因此基于高斯正态分布模型的参数分类算法 MLC 是明显不适合,建议考虑选择 ANN 分类法、决策树、基于专家知识分类法等先进的非参数分类器;其次如果使用中低分辨率影像数据时,混合像元现象明显时需考虑使用光谱混合分析法(SMA)或模糊集分类法(Fuzzy-set)等亚像元或软分类法;当使用高分辨率影像时,选择基于对象分类法(object-based classification)要优于基于像元分类法(pixel-based classification);④结合辅助数据,尤其是 DEM 数据能显著地提高山区遥感植被或森林制图精度。除海拔信息以外,其它地形属性,如坡度、坡向、坡型、坡位等等也是重要的辅助信息。另外随着高分辨率数据的广泛使用,纹理、形状以及关联信息成为有必要考虑的重要辅助信息。⑤精度评估是影像分类过程中不可缺的部分。尽管模糊法对评估模糊分类结果上获得了关注,但基于误差矩阵的精度评估是评估基于像元分类中最常用方法。

总而言之,成功进行山区影像分类,并完成高精度植被制图需依赖诸多因素。高质量的遥感影像数据、高质量的训练样本、可获得的辅助数据、完善的分类程序设计、分析者的能力与经验等都非常重要。现如今,由于缺少选择准则和合适可用的分类算法,很难确定最佳分类器,所以将来还有必要针对主要分类算法和分类器发展一个普适可用的指导准则。随着遥感卫星技术的发展,越来越多的高分辨率遥感数据广泛使用,随之带来的阴影效应,分类算法等问题都需要得以进一步开发和发展。将 GIS 技术与遥感数据结合是提高遥感植被制图精度的一个发展方向。此外,影像处理过程中不确定性和误差传递是影响分类精度的重要因素。不确定性研究是将来遥感影像分类研究中一个重要的课题。未来研究还需要将群落和植被生态学的理论和方法与遥感技术相结合来提高山区植被制图精度,乃至促进遥感科学和空间植被生态学发展。

参考文献:

- [1] 宋永昌. 植被生态学[M]. 上海:华东师范大学出版社,2001.
SONG Y C. Vegetation Ecology [M]. Shanghai: East China Normal University Press,2001.
- [2] 赵英时. 遥感应用分析原理与方法[M]. 北京:科学出版社,2003.

- ZHAO S Y. The principle and method of analysis of remote sensing application [M]. Beijing: Science Press, 2003.
- [3] FABIO M, CLAUDIO C, LJIANA P et al. Inclusion of prior probabilities derived from a nonparametric process into the maximum - likelihood classifier [J]. Photogrammetric Engineering and Remote Sensing, 1992, 58 (2): 201-207.
- [4] BROWN D G. Predicting vegetation types at treeline using topographic and biophysical disturbance variables [J]. Journal of Vegetation Science, 1994, 5 (5): 641-656.
- [5] CRAVE E, GASCUEL-ODOUX C. The influence of topography on time and space distribution of soil surface water content [J]. Hydrological Processes, 1997, 11 (2): 203-210.
- [6] WESTERN A W, GRAYSON R B, BLÖSCHL G, et al. Observed spatial organization of soil moisture and its relation to terrain indices [J]. Water Resources Research, 1999, 35 (3): 797-810.
- [7] GÓMEZ-PLAZA A, MARTÍNEZ-MENA M, ALVADALEJO J, et al. Factors regulating spatial distribution of soil water content in small semiarid catchments [J]. Journal of Hydrology, 2001, 253 (1): 211-226.
- [8] FRANK T D. Mapping dominant vegetation communities in the Colorado Rocky Mountain Front Range with landsat thematic mapper and digital terrain data [J]. Photogrammetric Engineering and Remote Sensing, 1988, 54 (12): 1 727-1 734.
- [9] WEISS D J, WALSH S J. Remote sensing of mountain environments [J]. Geography Compass, 2009, 3 (1): 1-21.
- [10] LILLESAND T M, KIEFER R W, CHIPMAN J W. Remote Sensing and Image Interpretation [M]. 5th ed. New York: John Wiley & Sons, Inc, 2004.
- [11] LU D, WENG Q. A survey of image classification methods and techniques for improving classification performance [J]. International Journal of Remote Sensing, 2007, 28 (5): 823-870.
- [12] SCHOWENGERDT R A. Remote Sensing, models and methods for image processing [M]. 3rd ed. New York: Academic Press, 2007.
- [13] 李石华, 王金亮, 毕艳, 等. 遥感图像分类方法研究综述 [J]. 国土资源遥感, 2005, 64 (2): 1-6.
- LI S H, WANG J L, BI Y, et al. A review of methods for classification of remote sensing images [J]. Remote Sensing For Land & Resources, 2005, 64 (2): 1-6.
- [14] 王一达, 沈熙玲, 谢炯. 遥感图像分类方法综述 [J]. 遥感信息, 2006, 5: 67-71.
- WANG Y D, SHEN X L, XIE J. A review of remote sensing image classification method [J]. Remote Sensing Information, 2006, 5: 67-71.
- [15] PHINN S R. A framework for selecting appropriate remotely sensed data dimensions for environmental monitoring and management [J]. International Journal of Remote Sensing, 1998, 19 (17): 3 457-3 463.
- [16] JENSEN J R, COWEN D C. Remote sensing of urban/suburban infrastructure and socioeconomic attributes [J]. Photogrammetric Engineering and Remote Sensing, 1999, 65: 611-622.
- [17] PHINN S R, MENGES C, HILL G J E, et al. Optimizing remotely sensed solutions for monitoring, modeling, and managing coastal environments [J]. Remote Sensing of Environment, 2000, 73 (2): 117-132.
- [18] LEFSKY M A, COHEN W B. Selection of remotely sensed data [M]//WULDR M A, FRANKLIN S E. Remote Sensing of Forest Environments: Concepts and case studies. Boston: Kluwer Academic Publishers, 2003, 13-46.
- [19] ZHANG Z, DE Clercq M E, OU X, et al. Mapping dominant communities vegetation in Meili Snow Mountain, Yunnan Province, China using satellite imagery and plant community data [J]. Geocarto International, 2008, 23 (2): 135-153.
- [20] QUATTROCHI, D A, GOODCHILD M F. Scale in Remote Sensing and GIS [M]. New York: Lewis Publishers, 1997.
- [21] CINGOLANI A M, RENISON D, ZAK M R, et al. Mapping vegetation in a heterogeneous mountain rangeland using landsat data: an alternative method to define and classify land - cover units [J]. Remote Sensing of Environment, 2004, 92 (1): 84-97.
- [22] JENSEN J R. Introduction to Digital Image Processing: A remote sensing perspective [M]. 2nd ed. Piscataway, NJ: Prentice Hall, 1996.
- [23] LANDGREBE D A. Signal theory methods in multispectral remote sensing [M]. Hoboken NJ: John Wiley and Sons, 2005.
- [24] HUBERT-MOY L, COTONNEC A, LE DU L, et al. A comparison of parametric classification procedures of remotely sensed data applied on different landscape units [J]. Remote Sensing of Environment, 2001, 75 (2): 174-187.
- [25] CHEN D, STOW D A. The effect of training strategies on supervised classification at different spatial resolu-

- tion [J]. Photogrammetric Engineering and Remote Sensing, 2002, 68(11): 155-162.
- [26] MATHER P M. Computer Processing of Remotely - Sensed Images: An introduction [M]. 3rd ed. Chichester: John Wiley & Sons, 2004.
- [27] ZHANG Z. Quantification of vegetation change in upper and middle Mekong Watershed using spaceborne remote sensing data [D]. Belgium: Ghent University, 2011.
- [28] TOUTIN T. Geometric processing of remote sensing images: models, algorithms and methods [J]. International Journal of Remote Sensing, 2004, 25(10): 1893-1924.
- [29] SONG C, WOODCOCK C E, SETO K C, et al. Classification and change detection using Landsat TM data: when and how to correct atmospheric effect [J]. Remote Sensing of Environment, 2001, 75(2): 230-244.
- [30] GITAS I Z, DEVEREUX B J. The role of topographic correction in mapping recently burned Mediterranean forest areas from Landsat TM images [J]. International Journal of Remote Sensing, 2006, 27(1): 41-54.
- [31] ZHANG Z, DE WULF R R, VAN COILLIE F M B, et al. Influence of different topographic correction strategies on mountain vegetation classification accuracy in the Lancang Watershed, China [J]. Journal of Applied Remote Sensing, 2011, 5(1): 053512 - 053533.
- [32] SMITH J A, LIN T L, RANSON K J. The Lambertian assumption and Landsat data [J]. Photogrammetric Engineering and Remote Sensing, 1980, 46(9): 183-189.
- [33] CIVCO D L. Topographic normalization of landsat thematic mapper digital imagery [J]. Photogrammetric Engineering and Remote Sensing, 1989, 55(9): 1303-1309.
- [34] GU D, GILLESPIE A. Topographic normalization of landsat TM images of forest based on subpixel sun - canopy - sensor geometry [J]. Remote Sensing of Environment, 1998, 64(2): 166-175.
- [35] DYMOND J R, SHEPHERD J D. Correction of the topographic effect in remote sensing [J]. IEEE Transactions on Geoscience and Remote Sensing, 1999, 37(5): 2618-2610.
- [36] SHEPHERD J D, DYMOND J R. Correcting satellite imagery for the variance of reflectance and illumination with topography [J]. International Journal of Remote Sensing, 2003, 24(17): 3503-3514.
- [37] SOENEN S A, PEDDLE D R, COBURN C A. SCS + C: a modified sun - canopysensor topographic correction in forested terrain [J]. IEEE Transactions on Geoscience and Remote Sensing, 2005, 43(2): 148-159.
- [38] SOENEN S A, PEDDLE D R, COBURN C A, et al. Improved topographic correction of forest image data using a 3 - D canopy reflectance model in multiple forward mode [J]. International Journal of Remote Sensing, 2008, 29(4): 1007-1027.
- [39] HUANG H, GONG P, CLINTON N, et al. Reduction of atmospheric and topographic effect on landsat TM data for forest classification [J]. International Journal of Remote Sensing, 2008, 29(19): 5623-5642.
- [40] GAO Y, ZHANG W. A simple empirical topographic correction method for ETM + imagery [J]. International Journal of Remote Sensing, 2009, 30(9): 2259-2275.
- [41] LENOT X, ACHARD V, POUTIER L. SIERRA: A new approach to atmospheric and topographic corrections for hyperspectral imagery [J]. Remote Sensing of Environment, 2009, 113(8): 1664-1677.
- [42] KAWATA Y, UENO S, KUSAKA T. Radiometric correction for atmospheric and topographic effects on landsat MSS images [J]. International Journal of Remote Sensing, 1988, 9(4): 729-748.
- [43] HUGHES G F. On the mean accuracy of statistical pattern recognizers [J]. IEEE Transactions on Information Theory, 1968, 14(1): 55-63.
- [44] PRICE K P, GUO X, STILES J M. Optimal Landsat TM band combinations and vegetation indices for discrimination of six grassland types in eastern Kansas [J]. International Journal of Remote Sensing, 2002, 23(23): 5031-5042.
- [45] MYINT S W. A robust texture analysis and classification approach for urban land - use and land - cover feature discrimination [J]. Geocarto International, 2001, 16(4): 27-38.
- [46] OKIN G S, ROBERTS D A, MURRAY B, et al. Practical limits on hyperspectral vegetation discrimination in arid and semiarid environments [J]. Remote Sensing of Environment, 2001, 77(2): 212-225.
- [47] RASHED T, WEEKS J R, GADALLA M S, et al. Revealing the anatomy of cities through spectral mixture analysis of multispectral satellite imagery: a case study of the Greater Cairo region, Egypt [J]. Geocarto International, 2001, 16(4): 5-15.
- [48] ASNER G P, HEIDEBRECHT K B. Spectral unmixing of vegetation, soil and dry carbon cover in arid regions: comparing multispectral and hyperspectral observations

- [J]. *International Journal of Remote Sensing*, 2002, 23 (19) : 3 939-3 958.
- [49] LOBELL D B, ASNER G P, LAW B E, et al. View angle effects on canopy reflectance and spectral mixture analysis of coniferous forests using AVIRIS[J]. *International Journal of Remote Sensing*, 2002, 23 (11) : 2 247-2 262.
- [50] NEVILLE R A, LEVESQUE J, STAENE K, et al. Spectral unmixing of hyperspectral imagery for mineral exploration; comparison of results from SFSI and AVIRIS[J]. *Canadian Journal of Remote Sensing*, 2003, 29 (1) : 99-110.
- [51] PLATT R V, GOETZ A F H, et al. A comparison of AVIRIS and Landsat for land use classification at the urban fringe[J]. *Photogrammetric Engineering and Remote Sensing*, 2004, 70(7) : 813-819.
- [52] HOLBEN B N, JUSTICE C O. The topographic normalization effect on spectral response from Nadir – pointing sensors[J]. *Photogrammetric Engineering and Remote Sensing*, 1980, 46(9) : 1 191-1 200.
- [53] CIHLAR J. Land cover mapping of large areas from satellites; status and research priorities[J]. *International Journal of Remote Sensing*, 2000, 21 (6/7) : 1 093-1 114.
- [54] FANKLIN S E, WULDER M A. Remote sensing methods in medium spatial resolution satellite data and land cover classification of large areas[J]. *Progress in Physical Geography*, 2002, 26(2) : 173-205.
- [55] FOODY G M. On the compensation for chance agreement in image classification accuracy assessment[J]. *Photogrammetric Engineering and Remote Sensing*, 1992, 58(10) : 1 459-1 460.
- [56] ATKINSON P M, TATNALL A R L. Neural networks in remote sensing[J]. *International Journal of Remote Sensing*, 1997, 18 : 699-709.
- [57] MAS J F, FLORES J J. The application of artificial neural networks to the analysis of remotely sensed data[J]. *International Journal of Remote Sensing*, 2008, 29 (3) : 617-663.
- [58] 修丽娜, 刘湘南. 人工神经网络遥感分类方法研究现状及发展趋势探析[J]. *遥感技术与应用*, 2003, 18(5) : 339-345.
- XIU L N, LIU X N. Current status and future direction of the study on artificial neural network classification processing in remote sensing[J]. *Remote Sensing Technology and Application*, 2003, 18(5) : 339-345.
- [59] FISHER P. The pixel; a snare and a delusion[J]. *International Journal of Remote Sensing*, 1997, 18(3) : 679-685.
- [60] CRACKNELL A P. Synergy in remote sensing – what's in a pixel[J]. *International Journal of Remote Sensing*, 1998, 19(11) : 2 025-2 047.
- [61] FOODY G M, COX D P. Sub – pixel land cover composition estimation using a linear mixture model and fuzzy membership functions[J]. *International Journal of Remote Sensing*, 1994, 15(3) : 619-631.
- [62] BINAGHI E, BRIVIO P A, GHEZZI P, et al. A fuzzy set accuracy assessment of soft classification[J]. *Pattern Recognition Letters*, 1999, 20(9) : 935-948.
- [63] RICOTTA C, AVENA G C. The influence of fuzzy set theory on the areal extent of thematic map classes[J]. *International Journal of Remote Sensing*, 1999, 20(1) : 201-205.
- [64] WOODCOCK C E, GOPAL S. Fuzzy set theory and thematic maps; accuracy assessment and area estimation[J]. *International Journal of Geographic Information Science*, 2000, 14(2) : 153-172.
- [65] MERTENS K C, VERBEKE L P C, WESTRA T, et al. Sub – pixel mapping and sub – pixel sharpening using neural network predicted wavelet coefficients[J]. *Remote Sensing of Environment*, 2004, 91(2) : 225-236.
- [66] FOODY G M. Approaches for the production and evaluation of fuzzy land cover classification from remotely – sensed data[J]. *International Journal of Remote Sensing*, 1996, 17(7) : 1 317-1 340.
- [67] FOODY G M. Sharpening fuzzy classification output to refine the representation of sub – pixel land cover distribution[J]. *International Journal of Remote Sensing*, 1998, 19(13) : 2 593-2 599.
- [68] ZHANG J, FOODY G M. Fully – fuzzy supervised classification of sub – urban land cover from remotely sensed imagery: statistical neural network approaches[J]. *International Journal of Remote Sensing*, 2001, 22 (4) : 615-628.
- [69] SHALAN M A, ARORA M K, GHOSH S K. An evaluation of fuzzy classifications from IRS 1C LISS III imagery: a case study[J]. *International Journal of Remote Sensing*, 2003, 24(15) : 3 179-3 186.
- [70] ROBERTS D A, GARDNER M, CHURCH R, et al. Mapping chaparral in the Santa Monica mountains using multiple endmember spectral mixture models[J]. *Remote Sensing of Environment*, 1998, 65(3) : 267-279.
- [71] RASHED T, WEEKS J R, GADALLA M S, et al. Re-

- vealing the anatomy of cities through spectral mixture analysis of multispectral satellite imagery: a case study of the Greater Cairo region, Egypt [J]. *Geocarto International*, 2001, 16(4): 5-15.
- [72] LU D, MORAN E, BATISTELLA M. Linear mixture model applied to Amazonian vegetation classification [J]. *Remote Sensing of Environment*, 2003, 87(4): 456-469.
- [73] ADAMS J B, SABOL D E, KAPOS V, et al. Classification of multispectral images based on fractions of end-members: application to land cover change in the Brazilian Amazon [J]. *Remote Sensing of Environment*, 1995, 52(2): 137-154.
- [74] SHIMABUKURO Y E, BATISTA G T, MELIO E M K, et al. Using shade fraction image segmentation to evaluate deforestation in Landsat Thematic Mapper images of the Amazon region [J]. *International Journal of Remote Sensing*, 1998, 19(3): 535-541.
- [75] YANG J, WEISBERG P J, BRISTOW N A. Landsat remote sensing approaches for monitoring long-term tree cover dynamics in semi-arid woodlands: Comparison of vegetation indices and spectral mixture analysis [J]. *Remote Sensing of Environment*, 2012, 119: 62-71.
- [76] 崔耀平, 王让会, 刘彤, 等. 基于光谱混合分析的干旱荒漠区植被遥感信息提取研究——以古尔班通古特沙漠西缘为例 [J]. *中国沙漠*, 2010, 30(2): 334-341.
- CUI Y P, WANG R H, LIU T, et al. Extraction of vegetation information in Arid Desert Area based on spectral mixture analysis——a case in the Western Gurbantunggut Desert [J]. *Journal of Desert Research*, 2010, 30(2): 334-341.
- [77] DORREN L K A, MAIER B, SEIJMONSBERGEN A C. Improved Landsat-based forest mapping in steep mountainous terrain using object-based classification [J]. *Forest Ecology and Management*, 2003, 183(1): 31-46.
- [78] THOMAS N, HENDRIX C, CONGALTON R G. A comparison of urban mapping methods using high-resolution digital imagery [J]. *Photogrammetric Engineering and Remote Sensing*, 2003, 69(9): 963-972.
- [79] WALTER V. Object-based classification of remote sensing data for change detection [J]. *ISPRS Journal of Photogrammetry & Remote Sensing*, 2004, 58(3): 225-238.
- [80] CONCHEDDA G, DURIEUX L, MAYAUX P. An object-based method for mapping and change analysis in mangrove ecosystems [J]. *ISPRS Journal of Photogrammetry & Remote Sensing*, 2008, 63(5): 578-589.
- [81] DOBROWSKI S Z, SAFFORD H D, CHENG Y B, et al. Mapping mountain vegetation using species distribution modeling, image-based texture analysis, and object-based classification [J]. *Applied Vegetation Science*, 2008, 11(4): 499-508.
- [82] 欧晓昆, 张志明, 王崇云, 等. 梅里雪山植被研究 [M]. 北京: 科学出版社, 2006.
- OU X K, ZHANG Z M, WANG C Y, et al. Vegetation research in Meili Snow Mountain [M]. Beijing: Science Press, 2006.
- [83] HARRIS P M, VENTURA S J. The integration of geographic data with remotely sensed imagery to improve classification in an urban area [J]. *Photogrammetric Engineering and Remote Sensing*, 1995, 61(8): 993-998.
- [84] MURAI H, OMATU S. Remote sensing image analysis using a neural network and knowledge-based processing [J]. *International Journal of Remote Sensing*, 1997, 18(4): 811-828.
- [85] STEFANOV W L, RAMSEY M S, CHRISTENSEN P R. Monitoring urban land cover change: an expert system approach to land cover classification of semiarid to arid urban centers [J]. *Remote Sensing of Environment*, 2001, 77(2): 173-185.
- [86] LU D, WENG Q. Spectral mixture analysis of the urban landscapes in Indianapolis with Landsat ETM+ imagery [J]. *Photogrammetric Engineering and Remote Sensing*, 2004, 70(9): 1053-1062.
- [87] CONGALTON R G, GREEN K. Assessing the accuracy of remotely sensed data: Principles and practices: Boca Raton [M]. New York: Lewis Publishers, 1999.
- [88] FOODY G M. Status of land cover classification accuracy assessment [J]. *Remote Sensing of Environment*, 2002, 80(1): 185-201.
- [89] CONGALTON R G, GREEN K. A practical look at the sources of confusion in error matrix generation [J]. *Photogrammetric Engineering and Remote Sensing*, 1993, 59(5): 641-644.
- [90] POWELL R L, MATZKE N, DE SOUZA JR C, et al. Sources of error in accuracy assessment of thematic land-cover maps in the Brazilian Amazon [J]. *Remote Sensing of Environment*, 2004, 90(2): 221-234.
- [91] CONGALTON R G. A review of assessing the accuracy of classification of remotely sensed data [J]. *Remote Sensing of Environment*, 1991, 37(1): 35-46.

- [92] MULLER S V, WALKER D A, NELSON F E, et al. Accuracy assessment of a land - cover map of the Kuparuk river [Z], 1998.
- [93] STEHMAN S V. A critical evaluation of the normalized error matrix in map accuracy assessment [J]. *Photogrammetric Engineering and Remote Sensing*, 2004, 70 (6): 743-751.
- [94] 张志明, 欧晓昆, 王崇云, 等. 利用 3S 技术对梅里雪山地区植被制图的精度检验分析 [J]. *应用生态学报*, 2004, 15 (9): 1 517-1 522.
ZHANG Z M, OU X K, WANG C Y, et al. Accuracy analysis of vegetation mapping for Meili Snow Mountain area, northwest Yunnan, China [J]. *Chinese Journal of Applied Ecology*, 2004, 15 (9): 1 517-1 522.
- [95] SMITS P C, DELLEPIANE S G, SCHOWENGERDT R A. Quality assessment of image classification algorithms for land - cover mapping: a review and a proposal for a costbased approach [J]. *International Journal of Remote Sensing*, 1999, 20(8): 1 461-1 486.
- [96] FOODY G M, MATHUR A. A relative evaluation of multiclass image classification by support vector machines [J]. *IEEE Transactions on Geoscience and Remote Sensing*, 2004, 42(6): 1 336-1 343.
- [97] HARDIN P J, SHUMWAY J M. Statistical significance and normalized confusion matrices [J]. *Photogrammetric Engineering and Remote Sensing*, 1997, 63 (6): 735-740.
- [98] STEHMAN S V. A critical evaluation of the normalized error matrix in map accuracy assessment [J]. *Photogrammetric Engineering and Remote Sensing*, 2004, 70 (6): 743-751.
- [99] FINN J T. Use of the average mutual information index in evaluating classification error and consistency [J]. *International Journal of Geographical Information Systems*, 1993, 7(4): 349-366.
- [100] MASELLI F, CONESE C, PETKOV L. Use of probability entropy for the estimation and graphical representation of the accuracy of maximum likelihood classifications [J]. *ISPRS Journal of Photogrammetry and Remote Sensing*, 1994, 49(2): 13-20.
- [101] BINAGHI E, BRIVIO P A, GHEZZI P, et al. A fuzzy set accuracy assessment of soft classification [J]. *Pattern Recognition Letters*, 1999, 20(9): 935-948.
- [102] WOODCOCK C E, GOPAL S. Fuzzy set theory and thematic maps: accuracy assessment and area estimation [J]. *International Journal of Geographic Information Science*, 2000, 14(2): 153-172.
- [103] FOODY G M. Approaches for the production and evaluation of fuzzy land cover classification from remotely - sensed data [J]. *International Journal of Remote Sensing*, 1996, 17(7): 1 317-1 340.
- [104] RICOTTA C, AVENA G C. Evaluating the degree of fuzziness of thematic maps with a generalized entropy function: a methodological outlook [J]. *International Journal of Remote Sensing*, 2002, 23 (20): 4 519-4 523.
- [105] RICOTTA C. Evaluating the classification accuracy of fuzzy thematic maps with a simple parametric measure [J]. *International Journal of Remote Sensing*, 2004, 25(11): 2 169-2 176.
- [106] WILLIAMS J. GIS Processing of geocoded satellite data [M]. Chichester: Springer and Praxis Publishing, 2001.
- [107] PFEFFER K, PEBESMA E J, BURROUGH P A. Mapping alpine vegetation using vegetation observation and topographic attributes [J]. *Landscape Ecology*, 2003, 18(8): 759-776.
- [108] HÖRSCH B. Modeling the spatial distribution of montane and subalpine forests in the central Alps using digital elevation models [J]. *Ecological Modelling*, 2003, 168(3): 267-282.
- [109] TURNER M G, GARDNER R H, O' NEILL R V. Landscape ecology in theory and practice: pattern and process [M]. New York: Springer - Verlag, 2001.
- [110] FARINA A. Principles and methods in landscape ecology [M]. 3rd ed. Netherlands: Springer, 2006.
- [111] SHERMAN R, MULLEN R, LI H, et al. Spatial patterns of plant diversity and communities in alpine ecosystems of the Hengduan Mountains, Northwest Yunnan, China [J]. *Plant Ecology*, 2008, 1(2): 117-136.
- [112] 沈泽昊, 张时新, 金兴义. 地形对亚热带山地景观尺度植被格局影响的梯度分析 [J]. *植物生态学报*, 2000, 24(4): 430-435.
SHEN Z H, ZHANG X S, JIN Y X. Gradient analysis of the influence of mountain topography on vegetation pattern [J]. *Acta Phytocologica Sinica*, 2000, 24(4): 430-435.
- [113] 张志明, 王文礼, 欧晓昆, 等. 梅里雪山植被空间格局与环境因子关系分析 [J]. *云南大学学报: 自然科学版*, 2009, 31(3): 311-315.
ZHANG Z M, WANG W L, OU X K, et al. The correlation between vegetation spatial pattern and environmental factors [J]. *Journal of Yunnan University: Nat-*

ural Sciences Edition, 2009, 31(3): 311-315.

- [114] ELUMMOH A, SHRESTHA R P. Application of DEM data to landsat image classification: Evaluation in a Tropical Wet – Dry Landscape of Thailand [J]. Photogrammetric Engineering and Remote Sensing, 2000, 66(3): 297-304.
- [115] LIU Q, TAKMURA T, TAKEUCHI N. Mapping of boreal vegetation of a temperate mountain in China by multitemporal Landsat TM imagery [J]. International Journal of Remote Sensing, 2002, 23(17): 3 385-3 405.
- [116] MCLVER D K, FRIEDL M A. Using prior probabilities in decision – tree classification of remotely sensed data [J]. Remote Sensing of Environment, 2002, 81(2): 253-261.
- [117] BROWN D C E C, STORY M H, THOMPSON C C K, et al. National park vegetation mapping using multitemporal Landsat 7 data and a decision tree classifier [J]. Remote Sensing of Environment, 2003, 85(3): 316-327.
- [118] REN G, ZHU A, WANG W, et al. A hierarchical approach coupled with coarse DEM information for improving the efficiency and accuracy of forest mapping over very rugged terrains [J]. Forest Ecology and Management, 2009, 258(1): 26-34.
- [119] MATHER P M. A computationally – efficient maximum – likelihood classifier employing prior probabilities for remotely – sensed data [J]. International Journal of Remote Sensing, 1985, 6(2): 369-376.
- [120] MASELLI F, CONESE C, DE FILIPPIS T, et al. Integration of ancillary data into a maximum – likelihood classifier with nonparametric priors [J]. ISPRS Journal of Photogrammetry and Remote Sensing, 1995, 50(2): 2-11.
- [121] FOODY G M, CAMPBELL N A, TRODD N M, et al. Derivation and applications of probabilistic measures of class membership from the maximum – likelihood classification [M]. Photogrammetric Engineering and Remote Sensing, 1992, 58(9): 1 335-1 341.
- [122] BEGON M, TOWNSEND C R, HAPPER J L. Ecology – Form Individuals to Ecosystems [M]. 4th ed. Malden, USA: Blackwell Publishing, 2006.
- [123] OHMANN J, SPIES T A. Regional gradient analysis and spatial pattern of woody plant communities of Oregon forests [J]. Ecological Monographs, 1998, 68(2): 151-182.
- [124] DIRNBÖCK T, DULLINGER S, GOTTFRIED M, et al. Mapping alpine vegetation based on image analysis, topographic variables and Canonical Correspondence Analysis [J]. Applied Vegetation Science, 2003, 6(1): 85-96.
- [125] FRANKLIN J, WOODCOCK C E. Multiscale vegetation data for the mountains of southern California: Spatial and categorical resolution [M] // Quattorchi D A, Goodchild M F. Scale in remote sensing and GIS, Boca Raton, FL, US: CRC – Lewis Publishers, 1997: 141-171.
- [126] THOMAS V, TREITZ P, DENNIS J, et al. Image classification of a northern peatland complex using spectral and plant community data [J]. Remote Sensing of Environment, 2002, 84(1): 83-89.
- [127] HORNING N, ROBINSON J A, STERLING E J, et al. Remote sensing for ecology and conservation [M]. New York: Oxford University Press, 2010.
- [128] HURTT G, XIAO X, KELLER M, et al. IKONOS imagery for the Large Scale Biosphere – Atmosphere Experiment in Amazonia (LBA) [J]. Remote Sensing of Environment, 2003, 88(1): 111-127.
- [129] NYOUNGUI A, TONYE E, AKONO A. Evaluation of speckle filtering and texture analysis methods for land cover classification from SAR images [J]. International Journal of Remote Sensing, 2002, 23(9): 1 895-1 925.
- [130] PODEST E, SAATCHI S. Application of multiscale texture in classifying JERS – 1 radar data over tropical vegetation [J]. International Journal of Remote Sensing, 2002, 23(7): 1 487-1 506.
- [131] RAO P V N, SAI M V R S, SREENIVAS K, et al. Textural analysis of IRS – 1D panchromatic data for land cover classification [J]. International Journal of Remote Sensing, 2002, 23(17): 3 327-3 345.
- [132] LLOYD C D, BERBEROGLU S, CURRAN P J, et al. A comparison of texture measures for the per – field classification of Mediterranean land cover [J]. International Journal of Remote Sensing, 2004, 25(19): 3 943-3 965.
- [133] LUNETTA R S, BALOGH M E. Application of multi – temporal Landsat 5 TM imagery for wetland identification [J]. Photogrammetric Engineering and Remote Sensing, 1999, 65(11): 1 303-1 310.
- [134] OETTER D R, COHEN W B, BERTERRETICHE M, et al. Land cover mapping in an agricultural setting using multiseasonal Thematic Mapper data [J]. Remote Sensing of Environment, 2000, 76(2): 139-155.

[135] GUERSCHMAN J P, PARUELO J M, BELLA C D I, et al. Land cover classification in the Argentine Pampas using multi-temporal Landsat TM data [J]. In-

ternational Journal of Remote Sensing, 2003, 24(17): 3 381-3 402.

Mountain vegetation mapping using remote sensing

ZHANG Zhi-ming, ZHANG Zheng-kai, GUO Yin-ming, TAO Guo-qing, OU Xiao-kun

(Institute of Ecology and Geobotany, Yunnan University, Kunming 650091, China)

Abstract: Vegetation mapping is one of essential and fundamental topics of vegetation ecology study. Due to the complex and heterogeneity of mountain environments, vegetation mapping in mountainous region is a big challenge. This paper provides a brief introduction to the procedure of mountain vegetation mapping by using remote sensing. We focus on the current issues and practices of satellite image classification in mountain areas for improving the classification accuracy. This article suggests that ① in mountain areas, the classification accuracy can be significantly improved by training vegetation or land cover class with different spectral response patterns on different aspects or slopes; ② many the topographic corrections models can significantly improve the accuracy of image classification; ③ image classification for mountain areas, advanced non-parametric classifiers, such as neural networks, decision tree, or knowledge-based approach, should be the better choice. Fuzzy-set technique or spectral mixture analysis sub-pixel classification can be used to overcome the mixed pixel problem for the coarse and medium spatial resolution data. For high resolution data, object-based classification is the better choice; ④ ancillary data, particularly DEM data can be combined with remote sensing data for improving image classification or vegetation mapping in mountainous regions. Advanced topographic normalization model and image classification algorithm should be developed in future. Integration of remote sensing and geographical information systems (GIS) appears as a new research topic. Currently, there exists a need to establish the link between theories and practices of ecological research strategies on one side and remote sensing image analysis on the other side.

Key words: vegetation mapping; mountain environments; remote sensing