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山地森林的碳捕获潜力：从全球角度看地方景观的韧性
The Potential of Mountain Forests in Carbon Capture: A Global Perspective on Local Landscape Resilience

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摘要：在当今世界，森林是捕获碳以减少温室气体（GHG）净排放的主要场所，其通过这种方式减缓或扭转了全球变暖，从而缓和了变暖的负面后果。目前这种能力在多大程度上来自那些位于山地上的森林？这种能力是否可以或应该得到进一步的提升？怎样才能提高我们对山地森林碳捕获潜力的评估能力，以应对现在和将来的不同情况？许多国家已经承诺到 2050 年实现净零排放，主要是使能源生产中排放的 CO^2 不超过他们能够吸收、保留乃至封存的量。因此，封存与减排的合作关系被提升了，减排通过向核电和可再生能源的转变以及通过能源用户的效率来实现。此外，在我们寻找更清洁和更划算的能源技术时，封存提供了一个近期的缓冲。从长远来看，封存可能会变得更加有效，从而更能分担温室气体的减排任务。尽管相关研究日益增多，但是还没有形成一套针对海洋、湿地、土壤和森林生物群落的封存潜力的评估方法。探讨与山林封存潜力评估需求相关的必要性和隐患。提高山林碳封存潜力的决心取决于：1）实现这一目标的难易程度；2）实现这一目标的机会成本；3）可在山地景观上进行的替代性使用和活动的效果和相互关系；4）替代性的海洋和陆地碳汇的比较效果；5）能源部门本身的去碳方法的成效。

关键词：山地景观；全球变暖；碳封存；植树造林；碳平衡；温室气体排放；砍伐森林；反照率；碳中和

Abstract: The world's forests are today a prime venue for carbon capture to reduce net greenhouse gas (GHG) emissions and by this means to slow or reverse global warming and thereby to moderate warming's negative consequences. To what degree does this current capacity extend to forests on mountainous terrain? Can or should this capacity be further nurtured? How can we improve our ability to estimate mountain forest sequestration potential both now and in the future under alternate scenarios? Many nations are now said to have pledged to achieve net zero by 2050 by emitting no more carbon dioxide — principally in energy production — than they can absorb and retain, hence sequester. Sequestration is thus elevated in partnership with emissions reduction — the shift to nuclear and the renewables and through energy-user efficiencies. Sequestration moreover offers a near-term buffer as we search for cleaner and more cost-effective energy technologies. In the longer term sequestration itself may become more efficacious hence more able to share the burden of GHG reduction. Despite a burgeoning literature, however, methodologies have yet to evolve with which to gauge the sequestration potential of the oceans, wetlands, soils, and forest biomes. This narrative considers both the necessity and pitfalls associated with the need to estimate mountain forest sequestration potential. Just how determined must we be to elevate carbon sequestration potentials in mountain forests is found here to depend on 1) the ease with which such an end can be achieved, 2) the opportunity costs incurred in achieving this end, 3) the efficacy and mutuality of alternative uses and activities that could be pursued on mountain landscapes, 4) the comparative efficacy of alternate oceanic and terrestrial carbon sinks, and 5) the cost-effectiveness of decarbonization approaches in the energy sector itself.

Keywords: mountain landscapes; global warming; carbon sequestration; afforestation; carbon balance; greenhouse gas emissions; deforestation; albedo; carbon neutrality

在当今世界，森林是捕获碳以减少温室气体（GHG）净排放的主要场所，其通过这种方式减缓或扭转了全球变暖，从而缓和了变暖的负面影响。但是，这种能力在多大程度上来自那些位于山地上的森林？相对于与海洋、湿地、农业实践、技术相关的其他封存手段，或者相对于主要由化石燃料燃烧产生的温室气体的持续释放，山地森林的封存潜力是否具有影响力？在对山地景观的补偿方面，这种封存是否优于其他碳封存方式，或者优于与全球供暖 / 制冷、制造和运输相关的能源生产减排？提高韧性是为了在面对系统性冲击和压力时促使功能延续，就山林而言，这种冲击和压力来自气候变化本身以及人类侵占和资源开采[1]。山地始终是容易引起争议的景观，其本地化管理将倾向于照顾当地人的利益，无论是居民还是商业企业。碳封存可以带来超出本地范围的全球性益处，如欲将碳封存的重要性凌驾于其他土地利用活动之上，则需要区域或国家层面的介入，特别是在土地利用竞争最激烈的低海拔地区。

山地森林为碳封存提供了独特的机会，但同时也提出了挑战。它们的上游植被稀少，位置偏远，因而得到保护；它们的下游植被更为丰富，但受到的威胁也更大[2]。此外，森林的碳密度在时间和空间上都有很大差异，其目前的碳封存能力如何？由于加速排放、森林退化、土地使用竞争和气候变化本身，这种能力可能会随着时间的推移而发生什么变化？是否有更好的、成本更低的方法来实现同等的碳捕获效果，从而减缓地球变暖？笔者将回应上述问题，首先识别现有相关研究的空白，同时尝试将这些问题置于更大范围的山地景观韧性主题之中进行探讨[3-4]。

目前，各个山地区域正受到威胁，其完整性受到内源性和外源性的自然及人为干扰的损害。区分这2类干扰将有助于形成当今最迫切需要的政策干预：内源性干扰来自山地景观本身，因此可以进行本地化的政策处理；外源性干扰来自山地景观之外，其在影响这些景观的同时本身不会因此而改变。从这个角度来说，碳捕获可被视为山地韧性特征之一。调整治理结构以涵盖与山地韧性相关的主要因果关系，理当是一个必要的目标。但是，管理韧性的多个维度需要进行优先级排序，因为并非所有维度都能同时实现，有些甚或是相互排斥的。

1 温室气体、反射率和蓄热

从古气候学家使用古希腊人的粗略观察方法开始，对于极端天气事件和长期气候变迁的研究已经持续了数个世纪。当然，现在我们的观察、诊断和行动能力有了很大的提高，且这些能力正以前所未有的方式被应用于理解和解决全球变暖带来的挑战。20世纪60年代，对于因地球大气反射能力增加而产生的蓄热效应（即反射率）的认识，揭示了CO_2和其他温室气体导致大气整体变暖的潜在作用，以及这种整体变暖产生的极端后果[5]。在所有的温室气体中，CO_2是截至目前变暖效应最大和持续时间最长的。工业化之前的大气二氧化碳浓度为2.8×10^{-4}，如今这个值超过了4×10^{-4}。

目前大多数知情分析家认为，气候变暖所造成的全球社会成本将会非常高，以至于需要做出重大努力来阻止这种变暖趋势[6]。他们宣称，考虑到潜在破坏的规模，有理由进行大量投资以抑制乃至扭转这一趋势[7]。除了默许之外，我们还有2种可能的行动方案：1）从源头上减排，主要涉及化石燃料的燃烧[8]；2）通过在海洋、土壤、湿地和森林等主要碳汇中进行技术性捕获和吸收，减少大气中的温室气体。最近的研究表明，通过机械过程将碳从大气中移除并储存在地下是有一定前景的，但这一工序的可扩展性仍未得到检验。海洋储存了大量的碳，但其吸收能力正因气候变暖和酸化而受到损害，其中酸化会对可吸收CO_2的海藻造成伤害。湿地提供了额外的碳捕获场地——特别是沿海湿地，但它们的效果有限且难以人为操控，不过保护湿地仍然是一个高度优先事项。鉴于这些情况，森林是帮助我们捕获CO_2（主要的温室气体）和储存碳的最佳途径。被剥离了氧气的碳将会存留在森林、草原和牧场之下以及海洋深处，3.67 t的CO_2等于1 t的碳储存。

可能除热带以外，北方森林（泰加）是世界上最大的森林生物群落[9]，因而其碳封存潜力很大。该区域没有发生过严重的侵略性森林砍伐，尽管受到病虫害和火灾的威胁，它仍有可能借助全球变暖而恢复和扩展森林，从而扩大自己的碳吸收能力。在全球范围内，每年可能有13万km^2的林地消失，主要位于热带，大多是由于畜牧业和农业扩张而导致的[10]。全球温室气体排放的1/4来自热带森林的砍伐，超过了全球交通方面的总排放量[11]。

2 全球变暖的后果

CO_2只是4种主要的温室气体之一，但其体积却在所有的温室气体中是最大的，甚至其影响也是最大的。其他3种主要温室气体分别是甲烷（CH_4）、一氧化二氮（N_2O）和臭氧（O_3），其中甲烷是天然气的主要成分，其危害在短期内至少是CO_2的80倍以上，限制它的排放可以有效缓解全球变暖。如果没有温室气体，地球将变得寒冷。当大气向下的反射率超过向上的反射率时，地球的表面就会变暖，这对许多地方或许是不利的，但对某些地方却是有利的。事实上，随着谷物带向北转移、曾经冰封的北方海路被打开以及干旱区在水文方面获益，一些国家从气候变暖中发现了机会。然而，随着海平面上升，沿海平原和城市被淹没在不断加深的海洋中，其他一些地方将遭受痛苦。如果气候变暖不受控制，有些地方将变得不适合居住，所有物种的地理分布将发生变化。这些负效应有助于我们估算气候变暖的恶果，并证明我们为恢复更适宜的气候而必须承受的代价是合理的。对每个国家来说，这种计算方法是不同的，因此在集体行动上达成一致仍然是困难的。

每个国家都会受气候变暖的影响，但这些影响的组合方式会有所不同，随之而来的抵制进一步变暖的决心也将有程度上的不同[12]。对一些国家来说，变暖可能是有利的；对其他国家来说，气候变暖的后果将是灾难性的，如不适宜居住的温度。后者如果缺乏缓解气候变暖负面影响的财政支持或技术能力，则其通过与其他国家达成交易来对抗气

候变暖的决心将增强。面积小和欠发达的国家一般排放温室气体较少，因而无法在源头减排方面采取行动，也无法就此进行交易。一些易受气候变暖影响的国家可能在森林碳封存方面有极大的潜力，所以他们可能希望将这种潜力提供给其他受困于气候变暖趋势的国家。这种交易可能会变得越来越普遍，事实上碳市场正被作为一种争取多国参与温室气体排放管理的手段[7]。

3 碳封存与能源行业去碳化

源于化石燃料使用和水泥生产等工业过程中的温室气体减排仍然是许多国家的首要任务，碳封存对大多数国家来说不是一种替代方法，而更多是一种与温室气体减排配套使用的策略。这种相互作用是视情况而定的，任何一方的进步都会改变另一方的投资计算。这种互动是不对称，每一方还会受到其所在环境特有的其他因素的影响。

碳封存有生物、地质和化学作用3种形式。在生物形式中，森林是最重要的，其能力远远超过草原、牧场和湿地。人类可以提高每种区域的吸收能力，树木、草本、藻类等都能通过光合作用从CO_2和H_2O中获得碳水化合物并释放出O_2。伐木、耕作、放牧、燃料采集等人类活动都是改善碳吸收的机会，伐木产生的木材可以在建筑中封存碳，林业和农业生态系统可以培育土壤以提高碳封存[13-14]。太阳能、风能、水能及其他替代性能源可以取代燃料采集，特别是在发展中国家。停止排干湿地，可以提高湿地的碳封存能力。给海洋施肥会产生消耗碳的藻类水华，后者最终将死亡并下沉。虽然海洋是一个巨大的碳汇，但进一步吸收CO_2会继续降低海洋的pH值（即增加酸化），这将损害作为海洋中吸收碳的主要媒介的藻类生态系统，削弱其进一步吸收碳的能力。在地质形式中，我们有多种方法可以将碳导入地下，使碳封存具有必要的持久性。最后，还有一些技术性作用的可能性，其大多被归于“直接空气捕获”（Direct Air Capture, DAC）类别下。无机土壤也可以在干旱的沙漠地貌中以钙钛矿（即沉积岩）的形式储存碳元素。在上述形式中，森林的碳封存潜力最大。

联合国环境规划署《2019年排放差距报告》[15]对目前上升进入地球大气层的温室气体净排放量与实现2015年12月《巴黎协定》[16]目标所需的排放水平之间的差距进行了估算，其中2018年全球温室气体排放总量为55.3 $GtCO_2e$①。该报告还注意到，1 t的C相当于3 667 t的CO_2，因为气态的CO_2一旦被封存并脱去O_2就成了C。上述测算主要考虑了地球上的森林、湿地和海洋中的净碳封存。2018年，几乎70%的温室气体排放来自工业和化石燃料的燃烧。正如后来所观察到的，每年净释放的温室气体一部分来源于自然过程，其中一些可能是当森林中的净平衡为负值时被释放的，即未被吸收的剩余物在大气中的释放。为实现2015年《巴黎协定》的目标，2018—2030年间的年温室气体净排放量必须减少25%~50%。虽然没有绝对永久性的碳封存手段，但今天的挑战是如何减少温室气体在大气中的瞬间释放，同时推迟已封存的碳的最终释放，直到可再生能源能够取代化石燃料。此后，化石燃料的替代可能会降低碳封存的紧迫性，尽管自然发生的碳储量释放仍然会引起某种程度的变暖。

迄今为止，已有100多个国家承诺在21世纪中期实现零排放，但如何在各国之间分配这项任务却被证明是有争议的。中国在2018年的化石燃料相关排放总量接近14 $GtCO_2e$，是美国的2倍以上。在新冠肺炎疫情之前，中国的净排放一直在稳步上升，而除印度之外的其他大多数国家都正趋于平稳。然而，虽然在稳步下降，美国的人均二氧化碳排放量是全球最高的，超过了排在第二位的俄罗斯。2018年中国的人均二氧化碳排放量还不到美国的1/2，也低于俄罗斯和日本。值得注意的是，中国在20世纪90年代开始大规模植树造林，并对原有森林进行培育以使其恢复健康。随着中国的森林成熟到了吸收高峰期，上述努力可能已经抵消了该国近40年来超过20%的化石燃料排放量，这一点有待更多文献资料予以证实。

在减排与吸收这2种方法中，假如有一种更为便宜、更有成本效益、更容易实施且有足够的可扩展性，那么它将成为我们唯一的关注点。然而，这2种方法单独使用都是不够的，因而已经达成的共识倾向于将2种方法进行组合。碳封存（即碳捕获）可能是更便宜的选择，因而一些国家会为其森林景观争取碳信用，作为降低源头减排率的理由。减排计划通常是在国家层面上制定，在国家以下的行政层级以及非营利组织和企业实体范围内实施，有时也在地方层级共同发起。国际合作几乎是必不可少的，因为任何地区——也许除了前面提到的美国和中国等大国——单独行动都难以改变全球空气质量变化的进程，而且也没有任何机制可以让单独行动的大国从不愿意或根本无法行动的“搭顺风车”的国家那里收回成本。晚近实现工业化的国家认为那些较早实现工业化的国家应该承担更大的责任，因为他们的排放是大气中持续存在的温室气体的主要来源。

目前碳封存与其说是一种选择，不如说是一种与基于源头减排相互配套的一个策略。这一情况体现在《联合国气候变化框架公约》的准则中，这些准则最早在1997年的《京都议定书》中开始实施（2005年生效，2013年到期）。2012年的《多哈修正案》虽然遇到了阻力，但最终在2020年底获得了必要数量签字国的批准。在上述努力中，2个表示行动的缩写词出现了，即A/R（造林/再造林）以及REDD+（减少因毁林和退化而导致的排放量，包括各种森林管理工作）。贫穷的国家呼吁和坚持要求更大、更富有的国家带头，但在公平分配减排份额时，显然并非所有国家都赞成允许减免碳封存，尽管这种态度可能正在改变[17-18]。

森林景观是上述举措的主要对象，因为森林景观在温室气体减排方面被认为比其他植物生境更有用。目前存在4种基于森林封存的不同策略，它们的功用在各国之间以及在平地和山地之间存在差异。这些策略包括：1）停止砍伐森林，禁止将林地永久地转变为其他用途；2）减缓森林退化，以免降低其作为碳储存库的功效；3）提高森林的健康水平，提高其碳密度；4）植树造林，在边缘土地或荒地上有选择地重新种植最有效的树种和其

他地被植物。

虽然森林砍伐仍在继续，但我们仍有很大机会可以阻止这种衰退趋势。全球森林面积在 20 世纪 90 年代每年减少 8.3 万 km^2，在随后 10 年中降为每年减少 5.2 万 km^2，证明了小幅改善的存在。每个数字都是自然和人为增加值的总和，说明因耕作、放牧、伐木和其他土地使用而造成的森林破坏正在减少[19]。据估计，地球上可能有多达 2 000 万 km^2 的土地适合恢复为森林，其中一部分位于山地[20]。

4 作为净碳汇的森林

由于地球上的森林景观既能吸收碳，又能释放碳，所以它们与气候变化过程之间存在内在联系[21]。碳摄入量（+）减去输出量（–）的净值就是碳平衡，即森林碳循环的结果。只有当摄入量超过输出量（净值为正）时，森林才是一个碳汇。这种平衡由 3 个共同发生的过程组成：涉及光合作用的呼吸（利用阳光将 CO_2 和其他成分转化为生物质中的碳水化合物和糖）；地上（叶子、枝干和树干产生木制品）和地下（根部）的生物量生产；以及枯木和垃圾的腐烂产生土壤[22-23]。上述过程既影响气候变化，也受到气候变化的影响。碳封存——相当于阳极碳的净摄入——是一个短暂的、瞬间的系统状态，因为所有封存的碳最终都会逃到大气中，除非被转化或烧毁。当然，延迟释放可以为减少来自化石燃料燃烧的碳排放争取时间，这些化石燃料（煤、石油、天然气）本身在燃烧之前就处于地下封存的状态。

此外，变暖过程在某种程度上可能被“偏差放大”，因为这个过程本身可能是一种加速剂或抑制剂。例如，随着极地冰雪的融化，长期隐藏的泥炭沼泽会被暴露而释放出 CO_2。气候变暖在提高山地森林树线的海拔高程的同时，也可以改善树线以下的森林生境，这 2 种方式都会扩大森林面积。另一方面，如果伐木、火灾、物种灭绝、腐烂和耕种所释放的 CO_2 超过了森林呼吸的摄入量，可能会促使世界上的植物群加快生长，从而提高了未来的碳吸收。更为普遍的是，全球地面覆盖物将随着难以预测的气候变化而发生变化。近年来，亚马孙流域可能有 1/5 的平原森林被砍伐，这主要是畜牧和农业扩张的结果，事实上全球变暖可能增强了该流域对畜牧的吸引力，从而加速了森林砍伐。火灾已经进入内陆地区，其中不少是由于农民为了种地而清除亚马孙森林所引燃的，同时，由于巴西在 20 世纪 70 年代修建大范围公路网络及推动内陆城市发展，森林被进一步开辟，导致火灾更为易发。在亚马孙流域，我们见证了一个因土地利用竞争而引发恶果的典型示例，在那里商业活动是砍伐森林的一种重要诱因。包括山林在内的其他森林是地球的最后防线之一，即使雨林正在被修复。下文聚焦 2 个问题：山地森林在未来的碳封存中可能会起到什么作用？在提升这种作用时有哪些潜在的挑战？笔者将从土地利用竞争的角度来看待这些挑战。

5 山地森林的碳封存效果

为了评估那些促进山地森林碳封存的工作的效果，笔者首先建立了一个数量级来衡量山地森林的数量、与地球森林总量的对比、碳足迹和碳密度。根据这些数据，笔者将试图判断山地森林在处理全球温室气体排放方面的潜力，并将把这种潜力归结为土地利用竞争的产物，其中相互冲突的利用模式——但不一定是竞争对手——都在争夺空间。当不同用途的支持者争夺土地使用权的时候，这种竞争将呈现出各种不同的形式。

笔者采纳通行的山地定义，即海拔 2 500 m 以上的地区，加上海拔 300~2 500 m 的表面崎岖不平的地区[24-25]。在这些山地中，只有约 1/4（1 150 万 km^2）是森林[24]。正如瑞士发展与合作署（Swiss Agency for Development and Cooperation）所指出的：“除了那些常年特别干燥或寒冷的地区，森林在大多数山地都占有相当大的比例。以欧洲为例，森林覆盖了总山地面积的 41%，其中森林占比超过 1/2 的山地有阿尔卑斯山、巴尔干山、喀尔巴阡山、派勒斯山等，其他森林覆盖率特别高的山地包括阿巴拉契亚山脉、澳大利亚阿尔卑斯山、圭亚那高地以及中非、东南亚、婆罗洲和新几内亚的山地。”[26] 除此以外，还有北美洲的落基山脉、非洲中部和中国的山地以及中美洲和南美洲的安第斯山脉。但总的来说，山林只占地球陆地森林总面积（4 590 万 km^2）的约 1/4。

森林，特别是山地森林，是否适合作为封存碳的选项？首先考虑一下林地的总体规模和范围：地球上的陆地和水面面积之和为 5.1 亿 km^2，其中陆地面积接近 30%（1.53 亿 km^2），陆地面积中大约 30% 是森林（4 590 万 km^2），而这些森林中可能有 25% 生长在山地（1150 万 km^2）。山地森林的确切面积和品质尚不明确，如森林的碳密度肯定会随着海拔的升高而下降。北方森林无疑代表了山地森林的最大份额，如果我们确切知道这种森林的组成及其树下和土壤的碳密度，就有可能明确其碳封存的总体潜力[27]，但目前这还不可能。

让我们考虑一下全球碳封存的所有选项，包括发生在湿地、海洋和森林等主要储存地的碳封存。森林和海洋是每年地球上的主要碳吸收者，尽管海洋中储存的碳的累积量远远超过森林生物群落中的。据 IPPC[28] 估计，森林及湿地每年总共吸收约 10 $GtCO_2$，而海洋每年吸收约 8 $GtCO_2$[29]，这个数字可能正在下降。全球化石燃料的燃烧和水泥生产每年向大气中释放近 29 $GtCO_2$，而土壤退化的耕作方式每年又增加了 4 $GtCO_2$。近 1 500 万吨的 CO_2 仍然悬浮在大气中，没有被吸收。每年的二氧化碳总排放量中，几乎有 1/2 仍漂浮在大气中。

当然，森林对碳的年捕获率和总储存能力有所不同。森林碳密度最高的是北方森林生物群落，热带森林次之，再次是温带森林。由针叶树、桦树和杨树构成的北方森林在北极以南的寒温带地区占主导地位，与主要由针叶树森林和湿地覆盖的泰加林带相邻。湿地生物群落的平均碳密度（700 t/hm^2）超过了北方森林（400 t/hm^2）[30]。

因此，森林不仅在全球碳捕获工作中占有重要份额，而且是在所有选项中最可能通过人类干预而提高碳捕获作用的一个。事实上，地球表面有 20 亿 hm^2（2 000 万 km^2）的土地可能适合用于上述基于森林的环境修复

活动。今天，森林可能吸收了1/3的化石燃料燃烧产生的CO_2（每年近30亿吨，或33亿短吨）。在所有自然吸收（封存）的手段中，森林似乎拥有最大的潜力，实现方式包括在以前没有森林的地方植树造林、在曾经有森林的地方恢复森林以及扭转森林衰退，恢复性策略是通过施肥、推广韧性树种、保护现有林分免受火灾和虫害来加速林分的建立。

6 估算全球山地森林的净碳封存量

理论上，全球山林最大碳封存潜力的粗略值可以按照总面积与单位面积年吸收能力的乘积进行计算，但并不是所有的山地都有森林，而且目前的记录也不充分。如前所述，地球上有1 150万km^2的森林在山地，在全球范围内，树龄大于200年的北方森林每年封存约700 t/km^2 CO_2[31]，1 150万km^2乘以700 t/km^2，得到每年73亿吨（80.5亿短吨）的CO_2。

有许多原因导致山地森林的活力及其碳潜力存在很大差异。这些山地的主要部分远远高于树线，而且树线会随着气温降低而下移。北方森林等森林生物群落将与岩石上的贫瘠土壤交织在一起，而在低海拔地区伐木和某些娱乐活动将进一步削弱森林碳封存能力。陡峭的地形将遭受侵蚀和森林退化的影响，导致碳密度降低。在低海拔地区存在竞争关系的活动将争夺空间，这种对土地的竞争——土地使用的竞争——在温带和热带森林生物群落中将更有可能被寻求森林产品货币化或拾取柴火的贫困人口所包围。在海拔较低、碳含量较高的茂密森林中发生的火灾可能会更严重，在释放大量碳的同时也为未来几十年后长出新的森林做好了准备。坡向也同样会影响森林，使山坡免受全日照，并在一定程度上阻碍了植物生长。同时，较为茂密的林地不仅会减缓水土流失，还会调节当地的水文，为山下的居民和社区提供更稳定的水源。但是，假如我们提供资金将当地居民集中安置在浅山区，也会导致与农业（用于商业及维持生计）、采矿、伐木和燃料采伐有关的森林破坏性行为。

看起来，随着平地森林的增加，山地森林在碳封存方面可能会被认为作用不大。正如联合国粮食及农业组织的全球森林资源评估报告（Forest Resources Assessment, FAO）每5年1次记录的，世界各地的森林都在遭受威胁。在拉丁美洲（亚马孙、大西洋森林、大查科、塞拉多和乔科–达连）、东南亚（大湄公河）、非洲（刚果盆地和东非）和南太平洋（婆罗洲、澳大利亚东部、新几内亚和苏门答腊），森林消失和退化最为迅速。此外，商业化农业继续占用大片较平坦的林地，对热带生物群落中的森林砍伐和退化负有主要责任。在所有大规模的商业化农业中，大豆、棕榈种植以及畜牧是最不适合较平坦的林地的。伐木是森林退化的另一个主要原因。目前人们现在正在研究如何在上述情况下提高森林恢复率。气候变暖是森林退化和衰弱的一个独立原因，同时也是火灾的助燃剂。

7 山地森林的能力：要点重述

回到本研究开始时提到的与山地森林有关的问题。首先，目前世界上的山林在碳捕获方面的能力是什么？回顾之前引用的数据，地球上总共有大约4 590万km^2的林地，其中1 150万km^2（约25%）位于山地，据称全球森林每年可吸收10 $GtCO_2$。考虑到前面提到的森林碳平衡中的所有综合效应，山地森林的最大额外净碳吸收能力将是2.5 $GtCO_2$。如果全球化石燃料的使用每年产生约29 $GtCO_2$，那么其中约9%的产量将被山林所吸收。这一数字可能偏高，因为在全球总估算量中，热带雨林的作用已被平均化了，虽然其作用相对较大。同时，海洋、山地及湿地一起也未能捕获近10 Gt的CO_2，其尚漂浮在大气中的。虽然现在海洋的碳捕获能力受到酸化的限制，但由于极地融化，海洋的容量可能略有增加，但这不足以消除每年10 $GtCO_2$的赤字。

包括山林在内的森林是否可以发挥更大功效，以吸收这一额外量？也许可以。如前所述，地球上可能有2 000万km^2的土地被认为适合恢复森林。按照全球平均森林碳净封存率10 Gt CO_2每4 590万km^2或218 tCO_2/km^2计算，山地森林可以净封存额外的1.1 $GtCO_2$，这是假设适合开垦的额外山地与全球林地中的山林比例成正比。这一碳封存量将相当于目前每年飘入大气层的二氧化碳量的11%左右。这样的估计必然是初步的，因为所需更为多元的数据尚未被获取。结论则是，山林已经在碳封存中发挥了重要作用，如果适当地培育山林，这种作用可能会扩大。

其次，由于土地利用竞争和气候变化本身，这种能力将如何随着时间推移而发生变化？是否有更好的、成本更低的方法来实现碳捕获的同等效果，从而减缓地球变暖？如前所述，由于缺乏替代方案，任何进一项减少全球温室气体排放的措施都必须来自2个主要策略：1）从源头减排；2）在森林中进行封存。目前必须探讨下列问题：是通过降低化石燃料的碳密度或转向可再生能源来减少源头排放的成本更低，还是进行进一步封存的成本更低？如果主张后者，那么在各种封存策略选项中，哪些是最可行和最具成本效益的？哪些森林封存的投资方案是最好的？

从3个方面进行考虑有助于我们回答上述问题：1）哪种方法可以在政治上被接受；2）考虑到相关政府部门和非政府部门的能力，哪种方法最有可能被实施；3）哪种方法最具成本效益？具有封存潜力但缺乏行动资金的穷国将不得不利用较富裕国家的资源，这使全球政治计算变得复杂。这种计算可分为两部分：较富裕的国家会不会对较贫穷的国家进行交叉补贴，而贫穷国家是否会接受这样的外部参与并为此付出多大的国内成本？森林封存的方案根据地点、土地质量、对附近居民的影响、所选树种的适当性、当地政府监督森林管理的能力、现在和未来的气候条件等因素而有所不同。对于森林改良的倡导者来说，这些因素可被结合在一起对植树造林投资选址方案的可取性进行打分。这种打分被视为一种评价功能，其评价结果是关于某一用途或使用者的森林投资选择的比较权重。这种评价使单一用途的使用者能够判断不同土地对特定用途的相对吸引力。当相互竞争的使用者或用途争夺指定空间时，该评价也会起作用。这种相互比较构成了土地

功能区划的基础，这就是土地使用的竞争[32]。

这种竞争基于 3 种分歧：1）平地和山地之间；2）土地使用的不平等竞争者之间；3）发达国家和发展中国家之间。如果将这些差异囊括在一个类似维恩图解的关系中，当然会有一些缺失的单元。首先，平地森林在可达性和森林丰富度方面具有吸引力，但其土地的潜在用途或使用者之间的竞争可能很激烈。山地的偏远性和不可渗透性将减少潜在使用者的数量和类型，因此竞争可能不那么激烈，这使得山地可能更适合于需要大片土地的碳捕获。大多数山林是在没有人类作用的情况下自行发展起来的。但是扩大其范围可能需要积极的管理。

争夺林地的第 2 种分歧存在于强大利益集团与穷人之间。在这场竞争中，竞争者拥有不均等的能力来确保竞争优势。未掺入温室气体的“清洁”空气是一种公共资源，其价值几乎完全不属于当地，因此在当地竞争者的决策考量中没有得到重视。在发展中国家的山地及其周边地区，生活着大约 7.2 亿人。其中 7/10 的人生活在山地的最为乡野部分，在较小的山坡上勉强维持生计，同时从那些在有着更多工作机会和收入保证的遥远城市打工的居民获得汇款。对这些人来说，森林提供了木材燃料、水、自给自足的农业和放牧空间，以及采矿、农业、放牧、旅游和伐木的商业性工作[33]。森林与贫困的并存已经导致这些森林被破坏，事实上自 19 世纪中期以来世界上的森林面积已经减少了 30% 以上，而这一损失大部分发生在发展中国家。森林砍伐在 20 世纪 90 年代达到顶峰，每年的净损失率约为 8.3 万 km^2。自 2000 年以来，这个年净损失率已经下降，可能约为 40%，这是开垦活动、山地经济城市化和气候变化本身的结果。

国家背景构成了争夺山地及其森林的第 3 个分歧。一些国家缺乏足够的国内资源和组织能力来促进森林发展和加强碳汇，这对于提高全球森林碳汇能力是一个特殊挑战。越来越多的人认为，争取他们的参与需要在管理和资金方面予以援助[34]。对于不少国家需要给予诱导条件，因为碳封存的好处在很大程度上被视为是非本地的，在国内的回报率不足以吸引大量投资。

在发达国家与发展中国家的山地中，相当一部分区域位于国家或区域层级政府的管辖范围内。在这些情况下，政府本身就是所有者，因此在这些土地使用的任何谈判中均是本国最为主导的实体。许多国家政府签署了《巴黎协定》或最近的《波恩挑战》[35]②，协定要求签署国承诺在 2030 年前造林 3.5 亿 hm^2 并将其用于碳封存。为此，这些国家将根据这一目标来利用山地，使该目的凌驾于任何来自政府以外的诉求及相关投标之上。

世界银行已经成为推动对包括碳封存在内的环境服务进行支付的主要机构之一，同时其还通过发展拉丁美洲和非洲各国经济来阻止森林破坏[36]。然而，与土地利用竞争的标准概念不同，因寻求场地而进行竞争的森林使用者将通过一系列政治和法律手段来提出空间主张，这些手段是参与竞争的资本。土地所有者之间的狭义价格战显然不是笔者所考虑的。对林地（特别对山林地）的争夺涉及一些索赔者，这些索赔者的数量随着海拔高度的增加而减少。

8 结论性意见

包括山林在内的森林是碳封存的主要背景，也是应对全球变暖的部分“解药”。事实上，目前有人认为地球自身有能力减少温室气体排放，使地表温度在未来几十年内开始稳定，这比以前预期的要早得多，是一个最为乐观的前景[37]。然而全球温室气体零排放仍然是一个挑战，排放量增加的前景将使基于源头的减排和碳封存成为一个更加紧迫的目标，特别是在发展中国家。

在更好的管理方法和更大范围的跨国合作的辅助下，山地森林应该被视为任何未来解决方案的一个重要因素，但还要更多的信息才能采取行动。对山地森林的全部碳封存潜力的估算仍然只是一个猜想，亟须更多关于山地森林组成的时空变化的分类数据，从而衡量现有绩效和未来潜力。鉴于其困难的地形、不寻常的土壤特性、多变的阳光照射以及土地所有权和控制权的变化无常，山地森林是一个特别的挑战。假如净零碳可以实现，一定不能缺少包括山林在内的森林的重要贡献。

了解山林以及所有其他海洋和陆地碳汇的封存潜力至关重要，因为这些碳汇的总封存潜力越大，就越没有必要减少来自主要能源使用行业的碳排放。相反，所有碳汇的总封存潜力越低，就必须更加努力地减少基于源头的碳排放，这主要是在能源部门，但不限于此。这个话题是在与韧性山地景观维护、规划和设计相关的更大范围事务中提出的。提升韧性是为了持续保持能力，以面对系统冲击和压力。虽然碳封存只是该目标的一个部分。然而，许多相互竞争的土地所有者在寻求从山地韧性中获益，他们的诉求并不容易调和。我们在提高山地森林的碳封存潜力方面的决心取决于：1）实现该目标的难易程度；2）实现该目标所产生的机会成本；3）在山地景观上可以进行其他用途和活动的有效性和相互关系；4）相对于替代性的海洋和陆地碳汇的功效；5）能源行业去碳化方法的成本效益。

与运输、制造和建筑供暖 / 制冷的去碳化相比，或者与提高海洋、湿地和土壤的封存能力相比，包括山林在内的森林的潜在贡献可能是一种更为便宜和快速的方式[38]。从长远来看，能源行业的去碳化几乎总是必不可少的。零碳排放几乎肯定需要通过电气化（主要由核能和可再生能源提供燃料）和封存来实现。中国预计在未来 15 年内出售的大多数新车将是电动的。通用汽车公司承诺，到 2035 年只销售零排放的汽车。这些话题之所以被放在“山地韧性”这一题目之下，是因为维持和提高山地森林的碳封存能力必然要与山地景观规划和管理中所追求的其他目标相竞争，其中包括农业、资源开采、燃料采伐、旅游等。

笔者将山地森林的碳汇潜力视为一个问题。我们需要获取更多关于山地森林组成的时空变化的分类数据，以衡量现有表现和未来潜力。为了判断山地森林生物群落作为碳汇的功效，我们还需要进一步研究 3 个不同的森林过程，包括呼吸作用、生物质生产和

分配，以及生物质腐烂和土壤生成的化学计量。在上述状况下，“只见树木不见森林”的谚语显得尤为贴切。我们在了解个别树木的同时，也需要了解整个山地森林生物群落或生态系统的所有协同复杂性。由于山地森林及地球上所有其他地球碳汇的封存潜力随着时间的推移而变化，我们必须考虑到每个碳汇的韧性。如果某些碳汇出现问题，其他碳汇可能要承担更大的责任。如果化石燃料可以被其他能源以更具成本效益的方式所取代，那么碳汇可能会承担较少的责任。能源行业的碳封存和去碳化都受制于变化无常的人类意志、技术、气候、环境容量和其他因素的影响，因此它们也许是人类面临的倒数第二大挑战，因为每个方面的进展都将不可避免地遭受系统冲击，威胁到任何特定“瞬间”解决方案的韧性。基本的现实是，为防止全球变暖而必须采取的行动和条件在本质上是没有韧性的。在没有替代品的情况下，有权势的社会群体将继续挖掘和燃烧化石燃料。森林、海洋、土壤和湿地迟早会释放其所封存的碳，因为其碳储量的封存并不完全。在能源、气候、生物群落构成的“系统”中，很少有元素会永久保持不变。韧性——包括其位于山地的部分——将需要多种补救措施来维持系统性绩效，包括修复或替换系统中失效的元素，或用新的手段来实现以前的做法或条件所不能解决的目的。包括山林在内的全球森林保护地也许迟早会在这个由脆弱部分组成的复杂系统中出现，成为一种稳定的力量。在森林和气候科学的指导下，森林管理者、规划者和风景园林师应该引领我们共同努力，充分挖掘包括山林碳封存在内的森林潜力。

注释：

① 该度量单位中的“e”表示所有温室气体成分的等效性，以 CO_2 的重量表示，以千兆吨（Gt）为单位，其中 1 Gt 为 10 亿（1×10^9）t。CO_2e 一词是指所有温室气体类型的排放总量，以与这些气体等同的二氧化碳当量表示。

②《波恩挑战》是由森林管理委员会和私营企业推动的，这是一个致力于森林保护和重新造林的联盟。

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（编辑 / 王一兰）

The Potential of Mountain Forests in Carbon Capture: A Global Perspective on Local Landscape Resilience

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The world's forests are today a prime venue for carbon capture to reduce net greenhouse gas (GHG) emissions and by this means to slow or reverse global warming and thereby to moderate warming's negative consequences. But does this capacity extend to forests on mountainous terrain? Is the sequestration potential of mountain forests impactful vis-à-vis all other means for sequestration — associated with oceans, wetlands, agricultural practices, technological means — or in relation to the continual release of GHG's resulting largely from the combustion of fossil fuels? Is the sequestration pay-off on mountain landscapes sufficient to warrant its prioritization over either other means of carbon sequestration, or over reduction of emissions arising from energy production associated with heating/cooling (HVAC), manufacturing and transport the world over? To promote resilience is to engender perpetual functionality in the face of system shocks and stresses. In the case of mountain forests these originate in climate change itself as well as human occupation and resource extraction[1]. Mountains are invariably contentious landscapes. Localized management of mountain landscapes will tend to favor localized interests whether residents or commercial enterprises. Carbon sequestration confers a non-local, global benefit. The assertion of the primacy of carbon sequestration over other land-using activities will require regional or national intervention particularly at lower elevations where land use rivalries are most pronounced.

Mountain forests present unique opportunities but also challenges. Their higher reaches are sparcely vegetated yet remote, hence protected; their lower reaches, are more abundantly vegetated yet more at risk[2]. Forest carbon densities moreover are highly variant over both time and space. What is their current sequestration capacity? How may this capacity change over time, the result of accelerating emissions, forest degradation, land use rivalries, and climate change itself? Are there better less costly means for achieving an equivalent effect in carbon capture, hence the slowing of planetary warming? This brief commentary begins to answer these questions. In doing so it begins to identify lapses of research coverage while attempting to situate these questions within the larger rubrics of resilience in mountain landscapes[3-4].

Mountain terrain is today everywhere under duress, its integrity compromised by both natural and anthropogenic disturbances, both endogenous and exogenous. Establishing the divide between these two classes of effects will go a long way to shape the policy interventions most desperately required today. The endogenous are those originating within mountain landscapes themselves hence amenable to localized policy treatments. The exogenous originate beyond these landscapes, impacting them but not being affected as a result of these impacts. In this light, carbon capture is seen to be interposed among co-existent features of mountain resilience. Aligning governance structures so as to encompass principal causal relations regarding any of the multiple dimensions of mountain resilience is of course a necessary objective. But managing multiple dimensions of resilience requires prioritization since not all will be simultaneously achievable. Some are mutually exclusive.

1 GHG's, Albedo, and the Heat Trap

Extreme weather events and prolonged climatic shifts have been the object of study for centuries, beginning with the work of paleo-climatologists deploying the crude observational methods of the ancient Greeks. Today our powers of observation, diagnosis and action are of course substantially advanced and they are now being applied as never before to understand and address the challenges posed by global warming. Awareness of the heat trapping effect of increase in the reflective capacity of the earth's atmosphere — its albedo — pointed by the 1960's to the potential role of the accumulation of carbon dioxide (CO_2) and other GHG's in the planet's atmosphere leading to its overall warming and to the extreme outcomes that this condition is believed to engender[5]. Of all GHG's, CO_2 has had by far the greatest warming effect over the greatest duration. Prior to industrialization CO_2's atmospheric density was 280 ppm. Today it exceeds 400 ppm.

Warming's projected global societal costs are now deemed by most informed analysts to be so severe as to warrant a major effort to arrest this warming trend[6]. The magnitude of potential damage is said to justify large investments to dampen, then reverse the trend[7]. We have currently just two potential courses of action beyond mere acquiescence: cut emissions at the source, principally the combustion of fossil fuels[8], or reduce their presence in the atmosphere, through technological capture and by absorption in our principal carbon sinks — our oceans, soils, wetlands and forests. Recent efforts show some promise in removing carbon from the atmosphere via mechanical processes, then storing it below ground. Scalability of this procedure though, remains untested. While oceans store vast quantities of carbon their absorptive capacity is being compromised due to warming and to acidification which harms the very algae that absorb CO_2. Wetlands, coastal wetlands in particular, offer additional capability, but their effect is limited and difficult to manipulate through human agency. Their preservation remains a high priority however. Given these conditions, forests represent our best opportunity to capture carbon dioxide (CO_2), the principal GHG, and to store carbon. CO_2 is the object of capture. Carbon, stripped of oxygen, is what remains on the forest floor, under our grasslands and rangelands, and in the depths of our oceans. 3.67 tons of CO_2 equal one ton of stored carbon.

The Boreal Forest (taiga), is the world's largest such forest biome[9], possibly excepting the tropical, so its sequestration potential is great. It is not the principal nexus of the most deleteriously aggressive deforestation. At the same time the Boreal may offer an opportunity to expand its carbon absorbing capacity through forest recovery and expansion made in part possible by global warming itself, despite threats of pestilence and fire. Globally, perhaps 130,000 km^2 of forest land, mainly tropical, is lost annually, mostly to cattle ranching and agricultural expansion[10]. As much as one-fourth of the earth's GHG emissions result from tropical deforestation exceeding the total emission from the planet's transport sector[11].

2 Consequences Of Global Warming

Carbon dioxide is but one of four major GHG's, but of all it is the most voluminous if not the most potent. Joining it in this nefarious process of global warming are Methane (CH_4), Nitrous Oxide (N_2O) and Ozone (O_3). Methane, the main component of natural gas is over 80 times as harmful as CO_2 at least in the short term. Limiting it remains a very fruitful enterprise. Absent GHG's the earth would grow cold. But when downward atmospheric reflectivity exceeds upward reflectivity the earth's surface warms and uncomfortably so for many places but not all. Indeed some nations find opportunity in warming as grain bands shift north, northerly sea routes once frozen open, and arid places realize hydrologic benefits. Other places though, will suffer as oceans rise, and coastal plains and cities submerge in deepening oceans. Some will become uninhabitable if warming is unchecked. The geography of all living species will change. It is these net negative effects that help us to value or price the ill-effects of warming and to justify the expenses we will have to endure to restore a more hospitable climate. For each nation the calculus differs, so attaining agreement on collective action remains difficult.

Every nation will experience warming's impacts but the mix of impacts will vary as will the attendant degree of determination to resist further warming[12]. For some warming might appear advantageous. For others warming's consequences will be catastrophic and could include temperatures above the habitable. The lack of domestic financial or technological capacity in these places with which to mitigate warming's negative effect will only heighten the determination to confront warming through bargains struck with other nations. Smaller and less prosperous nations generally have the lesser rates of aggregate GHG production, and so cutting emissions at the source is not an action they can take, with which to bargain. A few of the more vulnerable may have inordinate potential, principally in forest carbon sequestration, so they may aspire to make this potential available to those other nations that are also burdened by warming trends. Such trades may become more commonplace. Carbon markets, indeed, are being pursued as one way to enlist multi-national involvement in emissions management[7].

3 Carbon Sequestration Versus Decarbonization of the Energy Sector

Reduction of GHG emissions, originating in the use of fossil fuels and in industrial processes like cement production, remains the priority of many nations, and for most sequestration is considered less as an alternative and more as a paired strategy in emissions reduction. The interplay is contingent. Advance on either side alters the investment calculus on the other though each is influenced by additional factors that are unique to its circumstance, so the interaction is asymmetric.

Sequestration takes three forms: biologic, geologic and chemo-mechanical. Of the biologic, forests are preeminent, offering capacity well in excess of grasslands, range lands and wetlands. Humans can improve the absorptive capacities in each area. Trees, plants, grasses, algae et al. all photosynthesize carbohydrates from CO_2 and H_2O releasing O_2 as a by-product. Such human activities as logging, farming, ranching, fuel harvesting and more all represent opportunities to improve carbon absorption. Logging yields lumber which sequesters carbon in buildings. Forestry and agro-ecosystems can nurture soils to improve carbon retention[13-14]. Alternate energy regimes — solar, wind, hydro, and others — can displace fuel harvesting, largely in the Global South. Ceasing to drain wetlands can improve their efficacy. And fertilizing the oceans could produce carbon-consuming algae blooms that eventually die and sink. While oceans are a massive carbon sink, the further absorption of CO_2 continues to lower the ocean pH (i.e. increases acidification), and this damages algae ecosystems — the principal agent of carbon absorption in oceans — weakening their capacity for further carbon absorption. Of the geologic option, there are various means for channeling carbon below ground into geologic formations having requisite longevity. And lastly there are technological-mechanical possibilities largely subsumed under the name of Direct Air Capture (DAC). Inorganic soils can also store carbon as carbonates in the form of caliche (i.e. sedimentary rock) in arid desert landscapes. None of the forest-alternatives noted here, as yet offers the sequestration potential of forests.

The UN Environmental Programme's Emissions Gap Report for 2019[15] estimates the difference — the "gap" — between current net GHG emissions rising into the earth atmosphere and the level of emissions that would be needed to achieve the goals of the Paris Agreement of December, 2015[16]. Total global GHG emissions were found to be 55.3 $GtCO_2e$ ① in 2018. Note further that one metric tonne of carbon (C) is equivalent to 3,667 metric tonnes of CO_2. Gaseous CO_2 once sequestered and stripped of oxygen is carbon. The measure takes into account net sequestration principally in the earth's forests, wetlands and oceans. Almost 70% of GHG emissions originated in industry and the burning of fossil fuels in 2018. As observed later, a portion of the annual net release of GHG originates in natural processes. Some indeed may be released when the net balance in forests is negative — denoting the atmospheric release of the unabsorbed surplus. Annual net emissions would have to be cut after 2018, from between 25 to 50% by 2030 to attain the goal of the Paris Agreement of 2015. While there is no means for carbon sequestration that can be said to be absolutely permanent, the challenge today is to diminish the momentary release of GHG's into the atmosphere while deferring the eventual release of stored carbon until renewables can displace fossil fuels. Thereafter the displacement of fossil fuels may lessen the urgency of sequestration though the naturally occurring release of carbon stocks could still induce some degree of warming.

Over one-hundred nations to date have pledged to achieve net zero emissions by mid-century. Apportioning this task among nations however is proving contentious. China's aggregate fossil fuel-related emission in 2018 approached 14 $GtCO_2e$, more than double that of the United States. China's net emission had been, pre-pandemic, rising steadily whereas that of most other nations, save India had been levelling off. US per capita CO_2 emissions, however, lead the world but are in steady decline, topping Russia, next in line. China's per capita CO_2 emissions, however, were less than half those of the US in 2018, at a level also exceeded by Russia and Japan. China, of note, in the 1990's began a large scale effort to plant new forests while nurturing older forests back to health. Such efforts may have offset upwards of 20% of its fossil fuel emissions four decades later as its forests matured into peak absorption. Further documentation will be useful.

If either approach — reduction versus absorption — were to be cheaper, more cost effective, easier to implement, and sufficiently scalable, it alone might be our sole focus. Neither approach alone though will be sufficient. Consequently, the emerged consensus favors the combination. Sequestration — carbon capture — may be the cheaper option so some nations seek credit for their forested landscapes when seeking to justify lower rates of source reduction. Emission reduction efforts are generally forged at the national level, implemented down the sub-national governing hierarchy and across a spectrum of non-profits and corporate entities, and at times co-originated at the local scale. International cooperation is almost essential because any region acting alone is unlikely to have the capacity to deflect the course of global change in air quality, possibly excepting the very largest nations including the United States and China, as noted previously. And there is no mechanism for large nations acting alone to recover costs from free-riding nations disinclined, or often simply unable to act. Late industrializers argue early industrializers should bear a larger responsibility due to the length of time in which their emissions were the principal source of persisting atmospheric GHG's.

Sequestration stands now not so much as an alternative as it is a strategic partner therefore, with source-based reduction. This reality is expressed in the aspirational precepts of the UN Framework Convention on Climate Change (UNFCCC) operationalized first in the Kyoto Protocol of 1997 (effectuated in 2005, expiring in 2013). The Doha Amendments of 2012 though met with resistance but eventually secured the requisite national signatories in late 2020. From these efforts emerged two distinct acronyms denoting action: Afforestation/Reforestation ("A/R"), and Reducing Emissions From Deforestation and Degradation

("REDD+" including various forest management practices). Poorer nations were vocal in their insistence that the larger, richer nations take the lead.

Clearly, not all nations have favored the allowance of sequestration off-sets when tabulating fair shares of emissions reduction though this attitude might be dissipating[17-18].

Forested landscapes are a principal target in these efforts because of the perceived utility of treed landscapes for this function, over other herbaceous habitats. There are four distinct forest-based sequestration strategies, and their utility will vary among nations and between flatland and mountainous terrain. These include: 1) halting deforestation — ceasing the permanent transformation of forest lands to other uses, 2) slowing forest degradation that renders them less efficient as carbon repositories, 3) enhancing the health of forests elevating their carbon densities, and 4) engaging in afforestation whereby marginal lands or wastelands are selectively replanted in the most efficacious tree species and other ground covers.

While the decimation of forests continues, there is considerable space available with which to halt this decline. Global forest area declined by 83,000 km^2 per annum during the 1990's. During the ensuing decade this figure fell to 52,000 km^2 per annum, evidencing marginal improvement. Each figure is the net of natural and human-assisted increase less losses due to forest destruction for farming, grazing, logging and other land uses[19]. It is estimated that there may be as much as 20 million km^2 of land on earth suited for forest restoration, some portion of which resides in mountains[20].

4 Forests as Net Carbon Sinks

Because the earths' forested landscapes both absorb and release carbon they are intrinsic to the processes of climate change[21]. The net of carbon intake (+) less output (–) is the carbon balance, the upshot of the forest carbon cycle. Only when intake exceeds output (net positive) is a forest a carbon sink. This balance is composed of three co-occurring processes: respiration involving photosynthesis, using sunlight to convert $C0_2$ and other ingredients into carbohydrates and sugar in biomass, biomass production both above ground (leaves, limbs, and trunks yielding wood products) and below ground (roots), and decay of deadwood and litter, yielding soils[22-23]. The processes noted both affect and are affected by climate change. Carbon sequestration — equivalent to net positive carbon intake — is an ephemeral, and momentary system state condition insofar as all sequestered carbon will eventually escape into the atmosphere unless transformed or cauterized. Delayed release of course, buys time to draw down source-based emissions emanating largely from the combustion of fossil fuels. Prior to combustion, of course, these fossil fuels (coal, oil, natural gas) themselves were in an underground sequestered state.

The process of warming moreover may in part be "deviation amplifying" inasmuch as the process itself can be an accelerant or a depressant. For example the exposure of long concealed peat bogs with the melt of polar ice will release CO_2. Warming could also elevate the demarcation of mountain forest tree-lines while also improving forest habitats below the tree-line, thereby in both ways expanding the forested area. On the other hand the release of CO_2 due to logging, fire, species loss, decay and cultivation in excess of that ingested in forest respiration could prompt faster growth of the world's flora thereby elevating future carbon absorption. More generally global ground cover will change, with climatic changes that will be difficult to predict. Perhaps one-fifth of the flat forested plains of the Amazon Basin has been deforested in recent years, mainly the result of cattle ranching and agricultural expansion. It is possible that global warming, in fact, enhanced the attractiveness of the Basin principally for livestock grazing, accelerating deforestation. Fires, many ignited by farmers clearing the Amazon forest for planting, have ploughed their way into the interior, made easier by Brazil's major effort to open up the forest in the 1970's, by building an extensive road network and fostering the growth of urban settlements in the interior. In the Amazon Basin we have a classic demonstration of the ill-effects of land use competition. There commercial viability is a substantial inducement to deforest the landscape. Forests elsewhere, including those on mountainous terrain are one of the planet's last lines of defense even as efforts to restore the rainforest are being mounted. Two questions are the focus of the remainder of this commentary. What may be the potential role of mountain forests in future carbon sequestration? What are the potential challenges in elevating this generalized forest potential in mountain forest biomes? These challenges are viewed through the lens of land use competition.

5 Efficacy of Carbon Sequestration in Mountain Forests

To evaluate the efficacy of efforts to promote mountain forest sequestration I first establish an order of magnitudes to gauge the quantity of forested lands in mountains, their size relative to the totality of the earth's forests, the carbon footprint of these mountain forests, and their carbon density. From these data I will seek to judge the potential of mountain forests to address global GHG production. And I will frame this potential as being a product of land use competition wherein rival uses, but not necessarily rival users, compete for space. Such competition will take widely different forms as the proponents of rival uses vie for the right to use land in particular ways.

I accept the prevailing definition of mountainous areas to be those whose elevation exceeds 2,500 meters above sea level or higher, plus those areas whose elevation is between 300 and 2,500 meters and whose surface is rugged and irregular[24-25]. Of this mountainous area, just one-quarter (11.5 million km^2) is forested[24]. As noted by the Swiss Agency for Development and Cooperation, "Forests cover a significant proportion of most mountain regions except those that are particularly dry or cold year-round. In Europe for instance, forests cover 41% of the total mountain area — over half of the Alps, Balkans, Carpathians, and Pyreness … . Other mountain regions with particularly high proportions of forest cover include the Appalachians, the Australian Alps, the Guiana Highlands, and the mountains of Central Africa, Southeast Asia, Borneo , and New Guinea” [26].

To these I would add the Rocky Mountains of North America, the mountain domains of central Africa and of China, and the Andes of Central and South America. But overall, mountain forests constitute just one-quarter of the total forested area set upon the earth’s land mass (45.9 million km^2).

Are forests, and mountain forests in particular, suitable candidates for emissions sequestration? Consider first the overall size and scope of forested lands. The earth’s surface over land and water is 510 million km^2. Close to 30% of this surface is land mass, or 153 million km^2. Of this land mass, around 30%, is forested, or 45.9 million km^2. And perhaps 25% of the earth’s forests reside in mountains, or 11.5 million km^2. The exact area is not definitively known, nor are the qualities of forested areas in mountains. Forest carbon densities, for example, surely decline with altitude. The Boreal forest undoubtedly represents the largest single share of the mountainous forest, and if we reliably knew the composition of this forest and the carbon density of its undergrowth and soils it would be possible to specify its overall potential in carbon sequestration[27]. This, however, is not yet possible.

Consider the full scope of global sequestration options including that occurring in its principal repositories: wetlands, oceans and forests. Forests and oceans are the earth’s principal carbon absorbers per annum, though the cumulative amount of carbon stored in oceans far surpasses that in forest biomes. The IPPC[28] estimates that forests, plus wetlands to a much lesser degree, absorb combined together around 10 GtCO$_2$ per year while oceans absorb perhaps 8 GtCO$_2$ per year[29], a figure that may be in decline. Global combustion of fossil fuels plus cement production release close to 29 Gt per year into the atmosphere, an amount augmented by another 4 Gt per year from soil-degrading farming practices. Close to 15 GtCO$_2$ remains suspended in the atmosphere, unabsorbed. Almost half of the total CO$_2$ emitted each year that is, remains adrift.

Forests of course vary both in annual capture rates and aggregate storage capacity. The highest forest carbon densities are found in Boreal forest biomes, with the tropical next and temperate forests lagging behind. Boreal forests of conifers, birch and popular predominate in the cold temperate region south of the Arctic, coterminous with the taiga which is largely covered in coniferous forests and wetlands. The carbon densities of wetland biomes (700 metric tonnes of carbon per hectare on average) exceed those of Boreal forests (400 metric tonnes per hectare)[30].

Forests then not only do a major share of the global work of carbon capture, but of all the options they offer the greatest opportunity for human intervention to elevate their role in carbon capture. Indeed, two billion hectares (20 million km^2) of the earth’s land surface might be suited for these forest-restorative activities. Forests today absorb perhaps one third (almost 3 billion metric tonnes per annum, or 3.3 billion non-metric (i.e. short tons) of the CO$_2$ produced by the burning of fossil fuels. Of all means for natural absorption (sequestration) forests appear to possess the greatest potential achieved through afforestation where no forest previously existed, reforestation to reclaim old forests areas, and the reversal of degradation. Restorative strategies include accelerating stand establishment through nutrient provision, promotion of resilient tree species, and protection of extant stands from fire and pestilence.

6 Estimating Net Carbon Sequestration in Global Mountain Forests

A rough approximation of the maximal sequestration potential of global mountain forests could in theory be computed as a product of area multiplied by annual absorptive capacity per unit of area, but not all mountain area is forested and current documentation is inadequate. There are, as previously noted, 11.5 million km^2 of forested land in the earth’s mountains. Further it is estimated that global boreal forests that are 200 years old or older, sequester around seven tons of CO$_2$ per hectare per year, or 700 tons per km^2[31]. Eleven and one-half million km^2 times 700 tons per km^2 yields 8.05 billion U.S. tons of CO$_2$ or 7.3 billion metric tonnes of CO$_2$ per annum.

There are many reasons why there is high variability in viability of mountain forests and their carbon potential. Major portions of these mountains will rise well above tree-line. And the tree-line itself will fall to lower altitudes as temperatures fall. Forested biomes such as the Boreal will be interspersed with patches of poor soils resting atop rocky outcrops, and at lower elevations logging and certain recreational pursuits will further erode sequestration capacity. Steeply sloped terrain will suffer erosion and forest degradation leading to lesser carbon densities. At lower altitudes rival pursuits will vie for space. This competition for land — land use competition — in both temperate and tropical forest biomes will be more likely to be surrounded by impoverished populations seeking to monetize forest products or scavenge for firewood. Fires in the denser forests at lesser altitudes having higher carbon content may burn hotter, releasing droves of carbon while preparing the ground for new growth in ensuing decades. Slope aspect will similarly shape forest outcomes, shielding the slopes from full sun and impeding growth somewhat. At the same time denser wooded areas will not only slow erosion but also modulate the local hydrology, furnishing steadier water supplies to residents and communities below. But furnishing the wherewithal for local populations to cling to the lower slopes will also promote destructive forest practices associated with both commercial and subsistence farming, mining, logging, and fuel harvesting.

It might seem that with the abundance of flatland forests, the work of mountain forests in carbon sequestration might be considered to be of less utility. Forests everywhere are under duress as documented every five years in the UN's Food and Agriculture Organization's Global Forest Resources Assessment (FAO). Areas of most rapid forest loss and deterioration are found in Latin America (Amazon, the Atlantic Forest, Gran Chaco, the Cerrado, and Choco-Darien), SE Asia (Greater Mekong), Africa (the Congo Basin, and East Africa), and the South Pacific (Borneo, Eastern Australia, New Guinea, and Sumatra). Moreover, commercial agriculture continues to claim large tracts of the flatter forested lands. It bears primary responsibility for deforestation and degradation in the tropical biome. Of all large-tract commercial agriculture, soybean, palm, and cattle grazing are most inimical in this area. Logging short of clear-cutting is another principal cause of forest degradation. More is being learned now about how to improve recovery rates in such settings. Warming operates as an independent source of forest degradation and decay while also serving as a fire accelerant.

7 Mountain Forest Capacity: Recapitulation

At the outset of this commentary several questions related to mountain forests were put forward. I return to those now. Firstly, what is the current capacity of the world's mountain forests in carbon capture? Recall from previously cited data that there are a total of about 45.9 million km^2 of forested land on earth at large, and of this amount 11.5 million km^2 (25%) resides in mountainous terrain. Global forests are said to absorb 10 GtCO$_2$ per annum. The absolute maximum additional capacity of mountain forests for net carbon ingestion, allowing for all the combined effects in the forest carbon balance noted earlier, would be 0.25 × 10GtCO$_2$, or 2.5 GtCO$_2$. If the global usage of fossil fuels produces around 29 Gt per annum, then around 9% of this production would be absorbed in mountain forests. This figure, moreover, may be on the high side given the greater role of tropical forests that has been averaged into these global aggregate estimates. At the same time, the combined sequestration of both oceans and mountains plus wetlands still leaves almost 10 GtCO$_2$ uncaptured and adrift in the global atmosphere. While the capacity of oceans at large, now limited by acidification, may increase marginally owing to polar melting, this would not be sufficient to erase the 10 GtCO$_2$ annual deficit.

Can forests including mountain forests do more to take up the slack? Perhaps they can. This is because, as already noted, possibly 20 million km^2 of the earth's land mass has been deemed suited for forest restoration. At the average global forest net sequestration rate of 10 Gt CO$_2$ / 45.9 × 10^6 km^2 or 218t CO$_2$ / km^2 mountain forests could net sequester an additional 1.1 Gt CO$_2$. This assumes the additional mountain land suited for reclamation is proportional to the ratio of mountain forest land to global forest land. This would amount to around 11% of the amount of CO$_2$ currently drifting into the atmosphere each year. Such an estimate is necessarily preliminary since the needed data — more disaggregated — are not yet available. It is concluded that mountain forests already play a vital role in carbon sequestration, and that this role might be expanded with proper nurturing of mountain forests.

Secondly, how may this capacity change over time as a result of land use rivalries and of climate change itself? And may there be better, less costly means for achieving an equivalent effect in carbon capture, hence the slowing of planetary warming? As noted already, given the lack of alternatives any further reduction in global GHG emissions will have to originate in just two principal strategies: 1) reduction at the source of emissions, and 2) sequestration, largely in forests. A succession of questions must now be asked. Is it less costly to reduce emissions at their source by reducing the carbon intensity of fossil fuels or by switching to renewables, or to engage in further sequestration? If the latter is advocated, then which among the options for sequestration are most feasible and cost-effective? And which of the forest sequestration investment options are best?

Three considerations help us to answer these questions: 1) which approach can gain political acceptance, 2) which is most likely to be implemented in light of capacities in both the involved governmental and non-governmental sectors, and 3) which is most cost-effective? Poor nations having sequestration potential but lacking the wherewithal to act, will necessarily have to draw upon the resources of wealthier nations complicating the global political calculus. This calculus is bifurcated. Will wealthier nations cross-subsidize the poorer? And will the poorer accept such external involvement and at what domestic cost? Forest sequestration options are differentiated in accord with location, land quality, impact on nearby resident populations, appropriateness of chosen tree species, capacity of local governments to oversee forest management, climatic conditions both now and in the future, and more. For the advocates of forest enhancements such factors as these combine together to score the desirability of alternate locational options for investment in afforestation and reforestation, and in arresting forest degradation. Think of this scoring function as an evaluation function whose output is a comparative weighting of forest investment options for a single use or user. Such evaluations allow single-use users to judge the relative attractiveness of different lands for a given use. They also come into play as rival uses or users "compete" for given spaces. Such comparisons constitute the basis upon which land is allocated to various functions. This is land use competition[32].

Three different divides define this competition: 1) between flatland and mountainous terrain, 2) among unequal contestants for the use of land, and 3) between the contexts of the Global North and South. Combined in a Venn-like diagram of course there will be some missing cells. First, flatland forests offer the attraction of both accessibility and forest abundance, but there the competition amongst potential uses or users of land can be intense. The remoteness and impenetrability of mountain terrain will tend to reduce the number and type of potential users and hence competition may be less fierce, making such places perhaps more suited for carbon capture which requires huge tracts of land. Most mountain forests have developed of their own accord, without human agency. But expanding these domains could require active management.

A second divide in the competition for forested lands is between large and powerful interests and the poor. In this competition contestants have unequal capacities to secure a competitive edge. And "clean" air, unburdened by an infusion of GHG's, is a common pool resource whose value is almost entirely non-local hence unappreciated in the decision calculus of local contestants.

In and on the perimeters of the mountainous regions of the Global South live perhaps 720 million people. Seven in ten of these live in the most rural portions of mountain terrain eking out an existence on the lesser slopes while securing remittances from residents who travel to distant cities where jobs are more plentiful and income more easily secured. For these persons forests provide wood fuel, water, space for subsistence farming and grazing, and commercial employments in mining, farming, grazing, tourism, and logging[33]. The juxtaposition of forests and poverty has taken its toll on such forest lands. Indeed, the area devoted to the world's forests has declined by over 30% since the mid 19th Century, and much but not all of this loss has been registered in the Global South. Deforestation peaked in the 1990's at a net loss rate of perhaps 83,000 km^2 per annum. Since 2000 this annual net rate has fallen, possibly by as much as 40%, the result of both reclamation activities, urbanization of mountain economies, and climate change itself.

National context constitutes a third divide in the competition for mountain land and the forests set upon it. Those nations lacking sufficient domestic resources and organizational capacity with which to promote forest development and enhance sequestration represent a particular challenge in elevating global capacities in forest carbon sequestration. Assistance, both management and financial, is increasingly seen to be needed to enlist their participation[34]. Inducements are needed in many instances in which sequestration's benefits are largely seen to be non-local, and in which the domestic payoff is therefore insufficient to engender substantial investment.

Considerable fractions of the terrain in mountains in both the Global North and South are in the province of national or regional governments. In these instances government per se is the owner hence the lead domestic entity in any negotiation over the uses of such lands. Many national governments, having signed on to the Paris Agreement or to the more recent *Bonn Challenge*[35] ② — which seeks national commitments to reforest 350 million hectares and to purpose them for carbon sequestration by 2030 — will dedicate their own mountain lands to this purpose, over-riding any claims and associated bids originating outside of government.

The World Bank has become one principal agent in promoting payments for environmental services including carbon sequestration while building domestic economies to forestall forest destruction in Latin America and Africa[36]. Unlike the standard notion of land use competition however, competing forest users seeking sites will muster an array of political and legal capacities with which to claim space. These attributes are the coin of competition. Narrowly defined price-competition among rival land claimants is clearly not contemplated in this discussion. The competition for forested lands, particularly on mountainous terrain, entails few claimants, their number diminishing with altitude.

8 Concluding Observations

Forests, including mountain forests, are a principal context in carbon sequestration and a partial antidote for global warming. Indeed some now believe that it is within the earth's reach to reduce GHG emissions to the point that surface temperatures may commence to stabilize in coming decades — far sooner than had previously been anticipated — , a most hopeful prospect[37]. Net zero global GHG emissions though remains a challenge and the prospect of rising emissions particularly in the Global South will make the pursuit of source-based emissions reduction and carbon sequestration an even more urgent but tandem objective.

Mountain forests, aided by both better management practices and greater cross-national collaboration, must be considered an essential element of any future solution. But to act more information is needed. Estimation of the full sequestration potential of mountain forests remains a matter of conjecture. More disaggregate data regarding the temporal and spatial variability of mountain forest composition will be required not only to gauge current performance but also future potential. Forests set upon mountains represent a particular challenge given difficult topography, unusual soil properties, variable sun exposure, and the vagaries of land ownership and control. Net zero carbon may be attainable but not absent the essential contributions of our forests including our mountain forests.

Knowledge of the sequestration potential of mountain forests and that of all other oceanic and terrestrial carbon sinks is of vital importance since the greater the collective sequestration potential of these sinks the less may be the need to reduce carbon emissions associated with the major energy-using sectors. On the other hand, the lower the aggregate sequestration potential across all sinks, the greater must be the effort to reduce source-based carbon emissions, primarily but not exclusively in the energy sector. This subject is set within the broader concerns associated with the maintenance, planning and design of resilient mountain landscapes. To promote resilience is to engender perpetual functionality in the face of system shocks and stresses. Carbon sequestration though is but one element of this pursuit. There are, however, many rival claimants seeking to benefit from mountain resilience and their quests are not easily reconciled. How determined must we be to elevate carbon sequestration potentials in mountain forests will depend on 1) the ease with which such an end can be achieved, 2) opportunity costs incurred in achieving this end, 3) the efficacy and mutuality of alternative uses and activities that could be pursued on mountain landscapes, 4) the comparative efficacy of alternate oceanic and terrestrial carbon sinks, and 5) the cost-effectiveness of decarbonization approaches in the energy sector.

The potential contributions of our forests including our mountain forests could represent a cheaper, faster way forward compared to the decarbonization of transport, manufacturing, and heating/cooling of buildings, or to elevating the sequestration capacities of the oceans, wetlands and soils[38]. In the longer term decarbonization of the energy sector will almost invariably be essential. Net zero will almost certainly require both decarbonization through electrification, largely fueled by nuclear and renewable energy sources, and sequestration. China anticipates that most new cars sold there in 15 years will be electric. General Motors pledges to sell only zero-emission vehicles by 2035. These topics are set within the rubrics of "mountain resilience" inasmuch as the maintenance and enhancement of the capacity for carbon sequestration in mountain forests necessarily must compete with rival purposes to be pursued in the planning and management of mountain landscapes. Among these are agriculture, resource extraction, fuel harvesting, tourism, and the like.

This commentary is a problematization of the carbon sequestration potential of mountain forests. More disaggregate data regarding the temporal and spatial variability of mountain forest composition will be required not only to gauge current performance but also future potential. Judging the efficacy of mountain forest biomes as carbon sinks will require further research into three distinct forest processes: respiration, biomass production and disbursement, and the stoichiometry of biomass decay and soil generation. The idiom that "one can't see the forest for the trees" is especially apt in this context. While we require knowledge of the individual tree we also need to understand the entire mountain forest biome or ecosystem in its full synergetic complexity. Because the sequestration potential of mountain forests and indeed all other planetary carbon sinks varies over time, the resilience of each must be taken into account. If some falter, other sinks may bear a greater responsibility. If fossil fuels can be supplanted by other energy sources in a cost-effective manner then carbon sinks may carry a lesser responsibility. Both sequestration and decarbonization of the energy sector are subject to the vagaries of the human will, technology, climate, environmental capacity and more. As such they represent perhaps the penultimate challenge facing humankind since progress in each facet will inevitably suffer system shocks threatening the resilience of any particular "momentary" resolution. The fundamental reality is that the actions and conditions that must be in place to forestall global warming are not intrinsically resilient. Powerful societal forces will continue, in the absence of alternatives, to unearth and burn fossil fuels. Forests, oceans, soils and wetlands will give up their sequestered carbon in time since the cauterization of their carbon stores will be imperfect. Few elements of the energy-climate-biome "system" are going to be held constant in perpetuity. Resilience, including that small piece of this system lodged on mountainous terrain, will require a multitude of remedies to maintain system performance. These include the repair or replacement of failing elements of the system, or the substitution of new means to achieve purposes that can no longer be addressed by prior practices or conditions. The protected domains of the earth's forests including its mountain forests might perhaps emerge in time as a steadying force within this complex system of vulnerable parts. Forest managers, planners, and landscape architects, informed by both forest and climate science, should be at the forefront of our collective effort to extract the full potential of forests, including mountain forests in carbon sequestration.

Notes:

① The "e" in this measure denoted equivalency across all the GHG components expressed in terms of the weight of carbon dioxide (CO_2), given in gigaton (Gt) metric, wherein one Gt is one billion (1×10^9) metric tonnes. The term CO_2e signifies aggregate emission across all GHG types, expressed in terms of their CO_2 equivalent.

② The Bonn Challenge is driven by the Forest Stewardship Council and private industry, an alliance bent on forest preservation and reforestation.

(Editor / WANG Yilan)