放牧家畜的践踏作用研究评述

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摘要：放牧家畜的践踏作用是家畜作用于草地的 3 个途径之一，相对于采食和排泄物的作用具有作用时间长、直接作用的草地组分多和效果持久的特点。家畜践踏损伤牧草、埋实种子、促进萌发，减少凋落物的现存量，增加土壤的紧实度、容重，降低土壤孔隙度、水稳性团聚体、透水性和透气性，导致雨后水涝和植物根区缺氧，引发水土流失。国内外使用的 4 种践踏强度指标分别存在不确定性大、忽视践踏强度的时间依赖性和畜种间差异、没有考虑放牧行为及其时间分配模式等问题，分析认为践踏强度应为家畜放牧行为、不同行为的持续时间、家畜体重、放牧地面积和坡度的函数。家畜的践踏作用因草地的健康状况差异而与之存在正或负的反馈机制以及践踏强度阈值，可能在草地退化和健康维护中起主导作用。今后需建立严格的研究方法和科学的践踏强度指标，重视草地植被对践踏的耐受阈限、践踏对牧草更新的调控机理及其对凋落物产生和分解的影响，以及土壤水分与践踏作用的关系，确定放牧系统的践踏强度阈值。

关键词：践踏；放牧；草地退化；植被；凋落物；土壤

A review on trampling by grazed livestock

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Abstract: Trampling is one of three ways for livestock to impact on grazing land is recognized to have longer active time and more permanent effect than intaking and excrement. It is therefore important to study the mechanism of trampling on grazing land in order to discover the mechanism of grassland degeneration and properly manage grazing ecosystems.

(1) Trampling on vegetation While the trampling of livestock physically damaged aboveground herbage and buried the seeds, it was determined to be beneficial to the germination and emergence of seedlings. Further effort and consideration should be given to the critical point of vegetation resistance to trampling and the basic understanding of feedback mechanisms between vegetation and trampling.

(2) Effects of trampling on litter Only two studies showed that trampling aided litter breakdown, by facilitating the infiltration of litter into the soil profile, thereby reducing litter accumulation. The effects of trampling on output and litter decomposition was however still unclear, indicating that further study may be required.

(3) Effects of trampling on soil The majority of studies focused on this phenomenon. There was the most studies on effects of trampling on soil. Trampling increased the compaction and bulk density of topsoil, while decreasing the porosity and water stable aggregates, air permeability and hydraulic conductivity. Within the studies, there was two disputes; one was that

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some studies showed that trampling resulted in a decrease in the compaction and bulk density of topsoil or no change, while another studies showed that trampling also changed the physical properties in deeper soil horizons. It is our opinion dispute has resulted from the difference in water content of topsoil and or the difference in response mechanism between topsoil and deeper soil respectively, a factor not considered in any studies. Further study should determine the critical value of soil water content while the physical properties of soil began to change because of trampling.

(4) Effects of trampling on run-off and soil erosion　Trampling caused low infiltration of topsoil and resulted in water logging and O_2 deficiency in the root zone after rainfall. When combined with the reduced coverage of vegetation and litter on soil surface, runoff and soil erosion increased. In our view, wind was also playing an important role in degeneration of grazing land of northern China, but there few studies on the effects of wind on soil erosion after trampling of grazed livestock. Furthermore, all studies had not paid attention to the protection of vegetation and litter from the damage of trampling on soil.

(5) Index of trampling intensity　Current studies have used 4 kinds of indices of trampling intensity. (a) Changes were noted in soil physical properties such as soil compaction and bulk density etc, but were not definite in different soil conditions. (b) Number or body weight of grazed livestock per hectare, but did not distinguish the trampling intensity of different grazing animals and their subsequent effects of grazing behavior on trampling. (c) Pass of human trampling on grassland. We consider the simulated trampling was fundamentally different from that of the grazed livestock. Moreover, the above 3 kinds of indices neglected the time-dependant dynamics of trampling intensity. (d) Body weight of livestock × grazing time Livestock per hectare. This did not take the grazing behavior of livestock and its time distribution pattern into consideration. We suggest that a proper index of trampling intensity should be the function of grazing behavior, persistence of different behaviors, body weight of livestock, area and slope of grazing land, however this will need be developed in future studies.

(6) Interrelationship between grazing intensity, the health of grazing land and trampling intensity　The feedback between grazing intensity and trampling intensity was stronger than a between grazing intensity and intaking. There was a positive feedback between trampling intensity and degeneration process in the degraded grassland, but a negative feedback in healthy grassland. This study concluded that the main factor impacting the degeneration of grazing land and its healthy duration should be trampling, and that there might exist a threshold value of trampling intensity.

In fact, most studies gave the comprehensive action of trampling, but did not properly account for the intaking and excrement of grazed livestock. Further studies on trampling need to develop a right experimental methodology and an index of trampling intensity be determined in order to exclude the interference of intaking and excrement. We conclude that there should be the more studies on the resistance threshold of herbage to trampling, the regulative mechanism of trampling on regeneration of herbage, the effect of trampling on litter and the interrelationship between trampling and soil water. Lastly, the threshold of trampling intensity should be confirmed on grazing land.

Key words: trampling; grazing; degeneration of grazing land; vegetation; litter; soil

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放牧管理不当是草原退化的主要人为因素。放牧家畜的践踏是家畜作用于草地的 3 个重要途径之一,以往研究草原的放牧管理,比较关注家畜的采食和排泄物的作用。实际上,一年中放牧草地只有 4%～20%和 1%～5%的面积分别被家畜的尿和粪覆盖,所以排泄物对整个放牧地的影响有限[1];采食虽然直接作用于牧草,但时间只占整个放牧期的 60%～70%[2],而且短期内难以改变草地群落组成,牧草可以通过再生长削弱其影响[3]。放牧家畜的践踏持续存在于整个放牧期间,除牧草外还直接作用于土壤,践踏损伤的牧草面积可以占到草地面积的 23%,对土壤的压力是链轨拖拉机的 2.7～5.3 倍[4];家畜高强度践踏 2～3d 的草地需要 6 个月才能恢复[5],翻耕的草地,绵羊践踏 40 周后便又逆转到压实状态[6]。因此,与采食和排泄物相比,放牧家畜的践踏有时间长、直接作用的草地组分多和效果持久的特点,对草地的影响可能更为全面和深刻。因此,探讨家畜践踏对草地的作用,有助于揭示放牧生态系统土-草-畜的相互作用机制,阐明放牧草地退化的生态学机理,发现主要诱因,优化放牧管理策略,为退化草地恢复、低践踏强度的家畜品种培育提供科学依据。本文通过综述国内外该领域的研究进展,结合放牧生态学的研究前沿加以评述,并提出值得进一步研究的问题。

1　家畜践踏对草地植被的影响

家畜践踏首先导致牧草的机械损伤。模拟试验显示,美国 5 个地区、不同海拔和地形的 18 种植物,对践踏的响应程度虽因种而异,但所有物种的相对盖度随践踏增强而逐渐下降,而且践踏后 1 年仍有 14 个物种未能恢复[7],牧草的形态学特征与其对

践踏的耐受性有密切关系[8]。在南非南部的放牧灌丛草地,Kemper 等发现面积较小的灌丛斑块更容易受放牧践踏的干扰[9]。其次,践踏能够埋实种子,有利于种子吸水萌发和出苗。Blumenthal 等在西澳洲比较了夏季绵羊践踏对 *Medicago murex* 两个品种出苗的影响,结荚小的品种容易受践踏而浅埋,因而出苗率高[10]。在高草普列里,晚冬放牧的肉牛促进当地土生禾草种的种子扩散,而且禾草春季萌发的实生苗比未践踏的草地增加 4 倍[11]。Winkei 等在美国亚利桑那州研究了肉牛践踏对 4 种禾草实生苗数量的影响,在中等以上降水年份,践踏促进一些物种的实生苗成活,效果与种子大小和气候关系密切[12,13]。在得克萨斯 Rolling 平原,肉牛践踏虽然对 *Panicum coloratum* 的实生苗密度没有显著影响,但 Weigel 等分析主要原因是出苗后降水不足以及幼苗对资源的竞争不利[14]。Harris 等认为绵羊践踏破坏地表草絮层也是促进种子萌发、出苗的重要原因[15]。

国内尚无这方面的报道。家畜践踏损伤牧草会改变草地植物的竞争格局,促进种子萌发可加速群落内种群的更新,引起群落结构与功能的变化。草地群落演替一定程度上可以看作是优势种的更替,研究植物种群对家畜践踏的抵抗力、恢复力和耐受阈值,有助于阐明放牧草地的演替规律,这是揭示草地退化机理的关键所在。

2 对凋落物的影响

在苏格兰高地,绵羊践踏加速草地凋落物破碎,减少凋落物的现存量[16]。在阿拉斯加的莎草草甸和杂类草草甸,雪鹅(*Anser caerulescens*)和加拿大鹅(*Branta canadensis*)将凋落物踏进土壤因而减少地表的凋落物量,但对群落中的立枯物量没有显著影响[17]。

国内尚无践踏对凋落影响的报道。上述两个研究结果,共同之处在于放牧践踏减少凋落物的现存量,不同之处在于前者的凋落物破碎后容易分解或流失,后者的凋落物被踏入土壤。目前还没有研究践踏对凋落物产生和分解的影响。凋落物是放牧生态系统元素循环过程重要的物质形态,还能缓冲践踏对土壤的破坏,保护植物生长点,加强这方面的研究有助于揭示放牧草地自我修复与健康维持机理。

3 对土壤理化性质的影响

家畜践踏首先改变土壤的紧实度[18],继而引发其它理化性质的变化。在美国得克萨斯州,冬小麦(*Triticum aestivum*)茬地放牧绵羊,践踏增加表土紧实度 40%以上[19],肉牛短期重牧,践踏减少土壤孔隙度和水稳性团聚体,引起透水性、透气性和水导率下降[20,21]。在新西兰,绵羊冬季践踏产生类似的效果[22,23]。在干旱的撒哈拉地区,绵羊和山羊践踏导致土壤结皮破碎,减少土壤结皮的面积,虽然重度践踏降低土壤渗透指数,但中等强度践踏却提高土壤渗透性;只有上层土壤容重下降,深层土壤不受践踏影响[24]。Kobayashi 等研究发现[25],家畜践踏虽然减少阳坡的土壤水分,但对阴坡土壤有效水无显著影响。

我国天山北麓的高山草地,放牧强度增加 1 倍,土壤紧实度提高 1.13 倍[26]。祁连山高山草原 10～40cm 土壤容重与牧压正相关,但放牧较重区域 0～10cm 土壤容重较小[27]。内蒙古典型草原,随着放牧强度增加,上层土壤容重和紧实度逐渐增加[28],土壤含水量下降,群落蒸发量随上层土壤紧实度增加而升高[29];贾树海等还发现表层土壤紧实度和土壤容重在轻度和中等放牧下增加,重牧之下却降低[30]。在中国西南岩溶地区,雨季放牧的绵羊对上层土壤的紧实度、土壤容重和土壤透性没有显著影响[31]。

放牧家畜对土壤的践踏作用是国内外集中报道的方面。当前的研究结果存在两点争议。第 1 点争议,表层土壤紧实度和容重对践踏的响应,有增加、减少和无明显影响 3 种试验结果。一般来说,土壤保持一定含水量时,践踏作用有压实效应;土壤水分匮缺时,践踏"蹄耕"表土的效应才能显现出来;少数研究中践踏不影响土壤物理性质的情况则属于压实与疏松之间的中间状态;Finlayson 等建模时甚至假设草地植被对践踏的敏感性与土壤水分正相关[32]。分析认为,土壤对践踏的响应依赖于土壤水分条件,土壤对践踏存在耐受阈限,但尚无有关报道,而且土壤对践踏的反应与水分的关系也未没有专项试验研究。第 2 点争议在于,多数研究认为践踏只影响表层土壤(<5cm 或 10cm),但是,祁连山高山草原 0～40cm 土层水分和速效氮含量在践踏强度梯度上的变化幅度有随土层加深而增大的趋势[27],任继周等也指出随着土壤湿度增加,放牧对草地生草土的破坏深度呈指数函数上升[4],仅仅研究草原上层土壤尚不足以获取全面、准确的草地放牧的践踏信息[27]。可以推测:(1)在家畜践踏过程中,土壤水分对于土壤物理性质的变化至关重要,土壤对践踏的耐受性随土壤水分而变化;(2)表层土壤和下层土壤对践踏的响应机制可能不同。这就需要揭示水分梯度上,不同土层土壤理化性质对践踏的响应规律,确定土壤对践踏的耐受阈值,尤其是不同践踏强度下"蹄耕效应"的土壤临界含水量和草地"路径"的形成机制。降水对草地土壤水分有决定性作用,是影响我国草原生产力的主要限制因子之一;在全球变化背景下,我国北方草地是对降水变化较为敏感的生态系统类型,把践踏对土壤影响与降水变化结合起来更有意义。土壤不仅是践踏直接作用的草地组分之一,还提供牧草生长的营养物质,过去"以草定畜"主要根据牧草供给量确定适宜载畜量,比较片面,考虑践踏对土壤的作用还应该"以土定畜",赋予"以草定畜"更为深刻的科学内涵。

4 对水土流失的影响

土壤上层紧实度增加,水分难以下渗,导致雨后水涝和根区缺氧,影响植物生长[21],加之地表植被和凋落物覆盖减少,容易产生地表径流,引起水土流失。新西兰,肉牛在冬季短期(2～3d)践踏后,在强降雨条件下,土壤固体悬浮颗粒、全氮、全磷的流失

量分别增加 87%、89%和 94%[5]。澳大利亚西部的草田轮作地,家畜夏季践踏减少地表的作物残茬和牧草残留物,在模拟强降雨条件下,径流量增加 2～16 倍、土壤流失量上升 10～14 倍,其中草地径流量和土壤流失量分别增加 2～4 倍和 6～7 倍[33];同样的绵羊放牧强度,自由放牧时家畜的践踏要重于轮牧,水土流失也更为严重。澳洲冬季湿润、夏季干旱,上述研究表明,不管放牧季节、时间长短、土壤水分如何,家畜践踏均导致土壤理化性质恶化,形成水土流失的潜在危害。但 Ruecker 等指出,如果家畜践踏没有严重破坏植被,土壤侵蚀量会小到可以忽略[34],内蒙古典型草原的径流量、土壤流失量也与植被盖度呈显著负相关[35]。

目前对水蚀研究比较多,而对风蚀研究较少。我国北方草原多风,草原破坏加剧沙尘危害是国内外关注的生态灾害,除了放牧家畜过度采食导致植被覆盖减少外,践踏破坏表土结构也是重要因素之一。因此这方面的研究还需与植被、凋落物对土壤的保护作用联系起来,以正确评估放牧对草地水土流失的影响,揭示我国草原区沙尘暴发生的生物学机制。

5　关于践踏强度指标

国外研究使用的践踏强度指标归纳起来主要有 3 种:(1)土壤理化性质的变幅,多用紧实度或土壤容重,也有土壤表面的性状变化[33],常用于研究践踏对土壤的影响;(2)单位面积放牧家畜的数量或体重,本质上是一种放牧强度的简化表示方法,多用于研究践踏对种子萌发、出苗的影响;(3)用人在草地上践踏不同的次数(Pass)模拟家畜的践踏强度。

国内研究所用的践踏强度指标也有 3 种。前两种与国外相同。第 3 种,用放牧草地上路径的密度、宽度、深度以及路径上植物数量和土壤容重 5 个土、草单项指标建立践踏综合指数(Comprehensive trampling index,CTI),结合草地载畜量,提出用单位面积草地上家畜体重与放牧时间的乘积($t \cdot d/hm^2$)表示践踏强度[27]。

分析国内外研究所使用的践踏强度指标。用土壤物理性状这种间接指标表示践踏强度具有很大的不确定性:(1)草地土壤对践踏的反应还受土壤类型、生草土发育程度、土壤水分、植物组成等因素的影响,生草土发育良好的草地,土壤变化就小[1],同一土壤若湿度差异较大,践踏后紧实度甚至发生相反的变化[6];(2)不同土壤性状对践踏的敏感性不一样,土壤紧实度、板结程度和大孔隙数量对践踏的敏感性高于土壤容重、水稳性团聚体和饱和水导率[21],而表层土壤的形状又高于土壤紧实度[36];用不同的土壤理化指标难以定量判断试验结果的差异是由于践踏强度不同、还是土壤内在属性各异。用人模拟家畜的践踏强度,优点是容易控制践踏强度,但人和家畜的践踏有本质区别,该方法适用于草坪等观赏类草地,要用于放牧草地还需改进。用单位面积放牧家畜的数量或体重表示践踏强度,考虑到践踏强度与家畜体重的关系是其合理之处,但不能反映践踏强度的畜种间差异和放牧行为对践踏强度的影响,譬如,在同一草地上放牧家畜的体重相同时,牛对土壤的影响要大于绵羊 1 倍[36],践踏强度随放牧强度而变化,对于家畜个体而言,主要由放牧行为的差异造成的,譬如家畜行走时至少一肢离地,在相同的放牧时间里,行走较多的家畜对草地的践踏强度要大。上面 3 种指标均忽略了践踏时间这一关键因素;绵羊自由放牧的践踏时间要比划区轮牧长 38.9%[37],因而对草地的践踏要重于轮牧[33];另一个显而易见的事实是,家畜放牧 3 天和 10 天,践踏强度不一样,这一点类同于放牧强度[1],而区别于压强的概念。践踏强度指标应考虑放牧管理的时间单元,有鉴于此,侯扶江等用单位面积草地上家畜体重与放牧时间的乘积表示践踏强度,应用于高山草原-甘肃马鹿放牧系统的研究取得了比较满意的效果[27],但是这个指标同样没有考虑家畜的放牧行为及其时间分配模式。

基于上述分析,践踏强度指标所应具备的诸多要素已经初步显现:除了有家畜体重、放牧时间和草地面积 3 项基本要素,还需考虑家畜的种类、年龄、放牧行为和草地地形等因素。践踏强度(Trampling intensity)可以定义为家畜放牧行为(b,如行走、奔跑、站立等)、不同行为的持续时间(t)、家畜体重(w)、放牧地面积(a)和坡度(s)的函数,$TI=f(b,t,w,a,s)$;在这里,不同种类和年龄的家畜在践踏强度上的差异通过体重反映出来①。在一定的践踏强度下,草地的不同表现反映草地内在属性的差异。应研究建立践踏强度与过去常用指标的定量关系,如放牧强度、草地生物量、土壤理化性质等,使不同草畜系统的研究结果具有可比性,便于在科研和放牧管理中使用。

6　践踏强度与放牧强度和草地健康的关系

内蒙古荒漠草原的放牧强度增加 40%和 1.2 倍,绵羊个体的践踏强度分别提高 20%和 26%,绵羊群体的践踏强度分别上升 67%和 2.8 倍,个体的采食量分别下降 16%和 33%,群体的采食量分别上升 17%和 49%[37]。典型草原的放牧绵羊有相似的变化趋势,当放牧强度比适宜放牧强度增强 1 倍时,个体和群体的践踏强度分别增加 23%和 1.4 倍,个体采食量减少 20%,群体采食量上升 61%[38]。可见,家畜个体和群体的践踏强度均随放牧强度增加呈上升趋势,主要原因是随着放牧增强、牧草不足,绵羊的觅食时间延长,行走步数增多。一般情况下,在过牧的温带草原,放牧绵羊的行走时间要比适牧下长 1/3～1/2[39],行走步数增多 14%[38]。家畜个体的采食量在过牧下减少,是因为重牧导致草地可食牧草不足,家畜通过增加行走、提高觅食速度以保

① 侯扶江,林慧龙. 放牧家畜的践踏强度指标. 待发表.

证觅食效率，却终不得一饱[4,40]。家畜群体的采食量虽然随放牧增强而增多，但增幅远远小于践踏强度。拟合模型显示，在过牧条件下，家畜践踏强度(Y_T)增幅与放牧强度(X)增幅的比约为 1.4($Y_T=1.42X-0.40$，$r=0.998$，$p<0.001$)，而采食量(Y_I)的增幅与放牧强度增幅的比约为 0.47($Y_I=0.47X-0.53$，$r=0.961$，$p<0.01$)，说明践踏作用对放牧强度的敏感性高于采食，它们之间的反馈作用也强于采食。

因此推测，当草地退化时，由于牧草不足，家畜行走时间和步数增多，践踏增强；同时，植被盖度和凋落物量下降，对土壤的保护作用减弱，放大了践踏的破坏作用，这又将加速草地退化；家畜践踏作用与草地退化存在正反馈机制。反之，当草地健康、牧草充足时，家畜无须通过增加行走而提高觅食效率，践踏强度下降；同时，良好的植被和凋落物又能缓冲践踏对土壤的破坏；家畜践踏与草地健康存在负反馈机制。放牧家畜的践踏作用可能在草地退化和健康维护中起主导作用，在草地退化和草地健康之间存在践踏强度阈值，今后的研究应确定不同放牧生态系统的践踏强度阈值，这是优化放牧管理策略的关键。

7 结束语

综上所述，国外报道了放牧家畜的践踏对植被、凋落物和土壤的影响，国内主要报道了践踏对土壤的作用。因为不能定量识别践踏与家畜其它放牧行为的关系、缺乏科学的践踏强度指标，绝大多数研究结果反映的是放牧家畜践踏、采食和排泄三者的综合作用，而且存在诸多争议之处，因而无法阐明 3 种作用的异同、揭示践踏作用的机理及其对放牧管理的指导意义，当务之急是建立践踏强度指标和严格的践踏试验方法。在具体内容上，需要研究草地植被状况与家畜践踏之间反馈机制以及对凋落物动态的影响、土壤水分状况与践踏作用的关系，确定放牧系统的践踏强度阈值。践踏能够将种子踏入土壤，破碎地表结皮和草絮层，促进种子萌发和出苗，即“金蹄子(gold hoof)”效应，但是践踏对牧草更新的调控机理及其对放牧管理的指示作用尚需深入研究。

在不同的草地健康状态下，家畜的践踏作用与之存在正或负的反馈机制，在草地健康管理中可能起主导作用。并且践踏作用对于草地植物种群更新、群落稳定和凋落物分解有重要作用。因此有必要对家畜践踏这一重要而又不受关注的“小”问题开展综合性、系统性的研究，为我国建立放牧管理的决策系统、实现天然草地的健康管理提供科学依据。

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