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Review

A review of permanent grassland grazing management practices and the impacts on principal Soil Quality Indicators.

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Abstract: Grasslands are at risk of degradation due to unsustainable management practices and climate change. Sustainable grassland soil management can promote ecosystem service delivery and improve the resilience of the entire grassland ecosystem to anthropogenic change. Here, we review the principal soil quality indicators (SQIs) and how they have been used to evaluate the sustainability of different grassland management practices globally. We then discuss sustainable grazing management practices, before reviewing some novel grassland species which may improve grassland resilience with relevance for grassland management in Europe and the UK. We also give an overview of current sustainable grassland management methods and their assessment at field scale. From this, we suggest that sustainable Grazing Management Plans (GMPs), together with the testing of drought-resistant grass species and appropriate SQIs monitoring, is key to increasing resilience of grassland ecosystems to anthropogenic change.

Keywords: Soil quality indicators, Grazing management, Ecosystem services, Permanent grasslands, Management practices.

1. Introduction

Grasslands cover more than 30% of total cultivated land in Europe and 69% globally [1], [2], and are generally recognized for their role in soil erosion control and ecological multifunctionality [3], [4]. Grasslands are experiencing degradation due to desertification and intensive grazing [5]. Grazing plays an essential role in grassland preservation and well-managed grazing can promote soil quality, biodiversity and other related ecosystem services [6]. Grazing affects the nitrogen cycle [7], soil organic carbon (SOC) [8], soil water content [9], bulk density (BD) [10] and soil biodiversity [11]. It can also promote several soil degradation processes affecting entire grassland ecosystems [12]. Overgrazing compacts soil and triggers a series of subsequent issues related to the increase in BD, such as soil loss, runoff and flooding [13], [14]. Moreover, soil compaction leads to depletion of SOC and total nitrogen affecting the soil microbiota [15]. For these reasons it is important to consider appropriate livestock densities that avoid these negative effects of overgrazing. However, the definition of heavy or light grazing, at a European level, may be too broad to assist farmers in their grazing decision-making. For instance, Klipple and Bement [16], define grazing density based on the ability of pasture species to maintain themselves as forage for grazing animals. However, this definition does not consider other soil quality indicators. Several studies discuss grazing advantages and disadvantages, synthesizing a large volume of scientific evidence, often providing a qualitative assessment of different grazing practices [17]. They generally focus on the comparison between different types of grazing management, i.e short duration grazing [18], continuous vs rotational grazing [19], holistic vs continuous grazing [20], and usually, they evaluate the impacts of practices on grass productivity [17].

Climate change is threatening grasslands globally by exposing soils to prolonged droughts, making it prone to soil erosion by water flow [21]–[23]. Heatwaves are also endangering global grassland productivity [24], particularly in semi-arid and arid climates where irregular and high-intensity precipitation is enhancing flooding and erosion [23]. Liu et al. [25] assessed grassland degradation worldwide, asserting that more than 45% of grassland areas have experienced degradation processes by human activities and climate change. Moreover, they stated that anthropogenic activities are more dominant in North America and Europe, while the Asian region is more affected by climate change. In the Chinese Loess Plateau, human activities and climate change contributed to 42% and 58%, respectively, of the total grassland degradation [22]. Currently, several studies explore the need to breed and select new drought-resistant grassland species to preserve the grassland provisional service [26], [27]. However, in the global context of climate change and less water availability for grassland, breeding of new drought-resistant grassland species can reduce yield gaps, bare soil conditions, and control soil degradation processes.

Soil quality is defined as the ability of soil to perform ecosystem functions [28]. It is a broad concept that is not limited to the biological, physical and chemical soil properties, but it also involves productivity and animal and human health [29]. The soil quality concept was introduced in 1977 by Warketin and Flacher [30], to respond to increasing stakeholder's concerns about soil resources and to evaluate land use decisions made in the institutional context. The interest in soil quality increased after the publication by Council et al. [31], when academia focused on critical soil function identification and a common soil quality assessment framework [29]. Nowadays, soil quality has obtained more attention for monitoring land management and sustainable development through the evaluation of the Soil Quality Indicators (SQIs) [32]. However, due to the wide complexity and site-specificity of soil quality, it is challenging to standardize the SQIs benchmark for a universal assessment. Indeed, there is no ideal or exact index value that can universally standardize soil quality assessment, but using a framework that prioritizes soil quality goals and evaluate the management operation to achieve those specific soil functions can help [28]. However, the cyclic estimation of SQIs can make farmers aware of the prominence of management, illustrating the interaction between anthropogenic practices and the natural circumstances affecting on soil [28]. Several farmer tools-kits have been developed to assess SQIs giving an overall evaluation of the main grassland functioning related to the soil ecosystem services delivery. Ditzler and Tugel [33], developed the "*Soil Quality Test Kit Guide*" providing a simple field assessment for 11 SQIs. This tool is potentially applicable for all agriculture and agro-forestry systems and permits a 3-level description of the main chemical, physical and biological SQIs. Visual soil assessment (VSA) is widely used and is known to be cost-effective, practical and to provide rapid results [34]. VSA gives reliable information about soil structure, presence of telluric fauna, soil porosity, root development tillage plan and soil colour. This information can be related to pH, BD, soil organic matter (SOM) and mean weight diameter of aggregates. However, for organic soils, soil structure is significantly correlated with pH, BD, and OM [35]. In this study, we aim to give a global perspective of grassland soil quality assessment and management, before applying the lessons with relevance to mitigate soil grassland degradation in European and UK. Firstly, we review the importance of SQIs for sustainable grazing management methods to avoid land degradation risk. Secondly, we present an overview of the new drought-resistant grass species that improve soil quality and reduce soil loss.

2. Soil Quality Indicators for grassland

SQIs are classified as biological, chemical, or physical in nature. Commonly used chemical indicators include organic/total carbon and nitrogen, extractable phosphorus and potassium, pH, electrical conductivity, and cation exchange capacity. Biological indicators include microbial respiration rates, microbial biomass, nitrogen mineralisation rates, macrofauna (often earthworms), nematodes, microbial community composition and enzymatic activity. Physical indicators include soil BD, structure, texture, aggregate stability, porosity, water storage, hydraulic conductivity and infiltration [36]. In relation to soil erodibility and flood risk reduction, the physical indicators are the most directly relevant, because they influence water storage capacity which sustains and regulates river flows, and thus contributes to stream flow buffering [37]. Nevertheless, many of the chemical and biological SQIs play important indirect roles through their influence on the soil physical properties. For instance, soil structure and aggregate stability both depend on SOC concentration, which in turn depends on a range of biological soil properties [38], [39]. As such, many of these SQIs are inter-related, and while physical properties are likely to have the biggest direct impact on soil erosion and flood risk, chemical and biological SQIs could serve as useful proxies to assess management. Bünemann et al.[40] showed that the most commonly used SQIs are water-holding capacity, water content, BD and texture. Historically, quantitative assessment of these physical SQIs was only possible with expensive and time-consuming analyses. SQIs related to soil hydraulic properties such as soil conductivity, water retention and hydraulic conductivity provide direct information on the ability of grassland soils to promote water infiltration instead of surface flow, thus reducing erosion. Several studies have assessed the soil hydraulic properties of grasslands and compared these to those of cropland soils. Abdalla et al. [41] reviewed the overall soil loss and SOC loss under different land uses, and found a remarkable protection capacity of grassland when compared to orchards, croplands, and forests. While total rainfall and slope were the key drivers of soil erosion, high soil surface cover, SOC and clay content all limited soil loss. Several studies accompanied SQI observations with measurements of SOM content and quality, due to its strong link with soil physical properties. SOM increases soil porosity, aggregate stability, promotes structure and increases the soil hydraulic conductivity [42]. Ghimire et al. [43] in the USA, among others, showed that SOC, microbial biomass and total nitrogen - the most commonly used SQIs [40] - were all higher under permanent grasslands compared to croplands, owing in a large part to the lower degree of soil disturbance in permanent grasslands. Lehtinen et al. [44] analysed the distribution of soil aggregates and assessed quality, quantity, and distribution of SOM in two unimproved and four improved (two organic and two conventional) grasslands in subarctic Iceland. They found a higher macroaggregate stability in organic farming practice compared with conventional farming, due to higher organic inputs. However, few attempts have been made to relate the type of vegetation cover to soil erodibility and SOC content and stock. Ravetto Enri et al. [45] highlighted the importance of grassland species composition in affecting SOC stock in Alpine pastures, while topographic attributes had negligible effects. Root characteristics are also important for increasing SOC stock, as well as determining the capacity of grasslands to resist erosion. Horrocks et al. [46] demonstrated a strong effect of forage species and variety on the aggregate stability, friability and SOC, in tropical environment grasslands in Colombia. These studies demonstrate the importance of vegetation type as a primary SQI to be considered when describing the potential of grasslands to reduce erosion. Whilst physical indicators provide a direct link to a grassland ability to reduce erosion, a large and increasing number of studies now emphasise the vital role of biological indicators on soil health and quality [36]. We believe this is another possible future development of indicators that link soil quality to its functioning as protection from erosion, and possible allow a rapid detection to start recovery before erosion takes place.

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3. Grazing management and soil quality

Sustainable grazing management practices aim to maintain or improve soil quality to prevent land degradation and increase biomass yield over time [47], [48]. As such, grazing timing, grazing density, time between grazing events, and livestock species are crucial considerations for the sustainable management of grasslands.

Grazing effects are species specific (animal/plant) and vary with management types, bioclimatic regions and soil properties [49], [50]. The interaction between climate and unsuitable farm management strategies, can compromise the soil status and thereby, promote flooding and erosion events [51], [52]. For instance, an increase in grazing intensity is generally related to a decrease in SOC, and conversely light grazing intensities ameliorates increases OM and reducing soil erosion events [53], [54]. Abdalla et al. [55] performed a meta-analysis on the effect of grazing intensity on SOC stock globally, highlighting a clear climate-dependent effect. They stated that in a dry warm climate, the grazing effect negatively influence the SOC stock at all levels except for light grazing which increases SOC by almost 6%, instead, in the moist climates, SOC declined in all grazing intensity management. Indeed, animal trampling compacts soil, destroying soil aggregates and altering the soil microbial community, boosting nitrogenous losses by denitrification, and therefore, contributing to grassland degradation [56], see Figure 1.

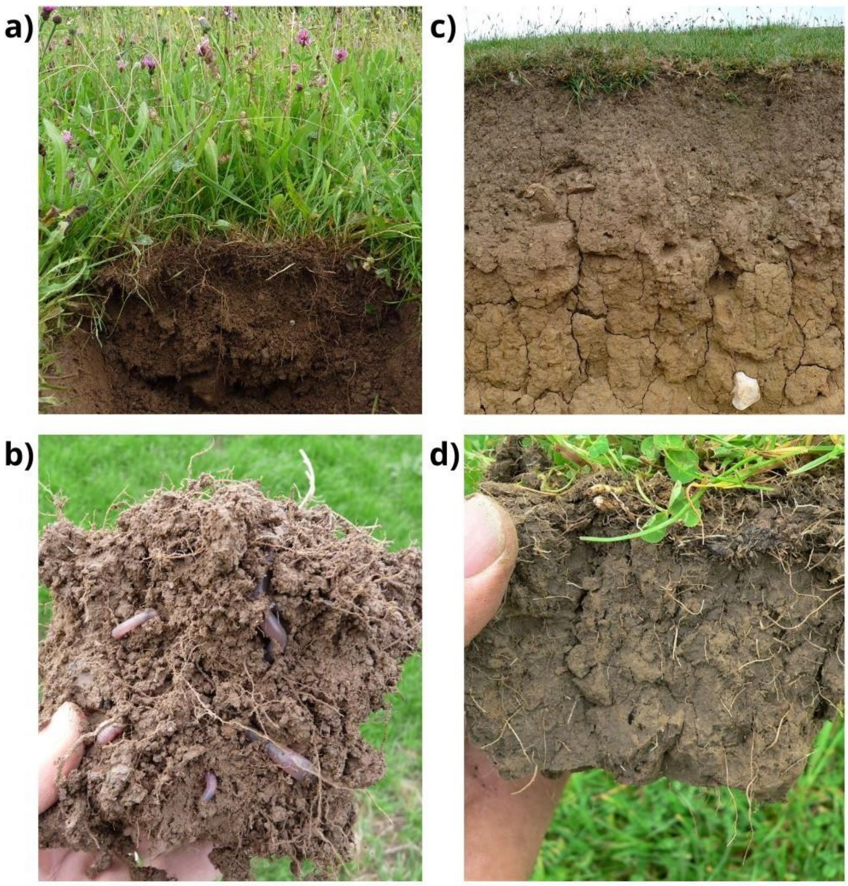

Figure 1. No-compacted grassland soil vs compacted soil (Northern England). a) zoom on no-compacted grassland soil; b) zoom on the non-compacted soil layer; c) zoom on compacted grassland soil; d) zoom on the compacted grassland soil layer (R. Smith 2023).

Devi et al.[57] in sub-tropical grassland, showed that medium grazing intensity promotes the nutrient cycle increasing, in this climate, grassland sustainability. Franzluebbers et al. [58], [59], in the Southern Piedmont USA, stated that long-term light grazing increases SOC, biological activity and soil quality. Many studies, across all the bioclimatic regions globally, stated that grazing intensity increases the BD, pH leading to higher

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denitrification processes raising soil erosion risk [60], [61]. Jiao et al. [62] instead analysed the effect of different grazing management types, asserting that heavy-grazing and no grazing management, significantly increase the BD compared to light and moderate grazing, underlining even more the positive effect of a well-controlled grazing management. Generally, heavy grazing is commonly recognised as the dominant factor that increases soil erosion and runoff generation in grassland [63], [64]. For instance, heavy grazing can promote runoff generation by up to 117% compared with rotational light grazing, while the latter has a positive impact in reducing flood risk [65], [66]. The choice of livestock breed is also important for farm productivity. New high-productive cattle breeds have different grazing behaviour and anatomic characteristics that impact grass composition and soil quality. Pauler et al.,[67]–[69] observed the grazing behaviour of low-productive cattle (Original Brauvieh) and high-productive breed Angus × Holstein in the Swiss Alps, highlighting some significant differences in grassland impact. The Original Brauvieh, on average, is 100 kg lighter than the high-productive breed and prefers to graze in flat areas close to the water point. Instead, the highly productive grazer roams long distances selecting higher-quality forage influencing the grassland species composition. Thus, grazing density and breed behaviour must be taken in consideration for the sustainable soil grazing strategies.

3.1 Grazing strategies for grassland soil conservation

In mountain regions of Europe eco-climatic, topographic and vegetation characteristics of pastures can widely vary even in small spatial ranges then affecting overall stocking rates and fine-scale livestock site use intensity [70]. In turn, animal excreta are heterogeneously distributed over the pastures, consequently influencing soil features, nutrient availability and biocycling and, thus, plant species composition. Defining a numerical threshold of each grazing management intensity is becoming an important need to prevent grassland degradation and mitigate the future soil loss and flooding hazard due to climate change. Therefore, the objective for sustainable grazing management should be to address the enhancement of grazing spatial distribution for a more homogeneous exploitation of the pastures by livestock. When livestock is allowed to roam freely, they show a selective and spatially aggregated grazing pattern [71], which leads to the overgrazing of most favourable areas (e.g. flat areas, near to water sources, etc.), Figure 2.

A Grazing Management Plan (GMP) is a tool that has been successfully adopted in North-West Italian Alps [72], [73] and funded by the 2007-2014 EU Rural Development Program with the purpose of enhancing farm productivity and, at the same time, preserving plant and animal biodiversity, soil, and landscape. To obtain a more even selection of available resources and hence reducing local overgrazing, GMP defines grazing management practices aimed at balancing the animal stocking rate with the grassland carrying capacity [74]. This means that, when considering the forage productivity and quality, grazing will occur over an area for a defined time period without causing degradation of the grazing land. To accomplish this, pastures are subdivided in paddocks grazed in rotation so that livestock is induced to homogeneously exploit the available resources while limiting overgrazing as much as possible [71]. However, different studies comparing continuous and rotational grazing found small differences between the two management regimes in terms of grass production, underlining the importance of stocking rate and climate condition as distinctive degradation drivers [75], [76]. Virgilio et al.[17] performed a meta-analysis on the effect of grazing strategies on different indicators of rangeland sustainability, such as vegetation dynamics and soil quality. They found that multiple species grazing before complete destocking can ameliorate the vegetation composition of the grass layer. Rotational grazing has a minor impact on the vegetation status compared to continuous grazing, even if the impact of the latter is strictly related to livestock density. Indeed, according to them, livestock density is the main factor of grass and soil degradation. Regardless of the grazing strategy, some measures can be applied to avoid grassland degradation, for example, attractive points such as drinking and feeding troughs and salt

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supplementations can be placed in underused areas (e.g. steep and shrub-encroached sites) to enhance livestock spatial distribution and reduce overgrazing in the most accessible sites [77]. Moreover, it is necessary to herd livestock into barns when the pasture soil is wet or saturated or, when possible, to reduce the length of the grazing period and to avoid rainy seasons. This minimizes the soil disturbance and can represent other valuable solutions to avoid overgrazing [63].

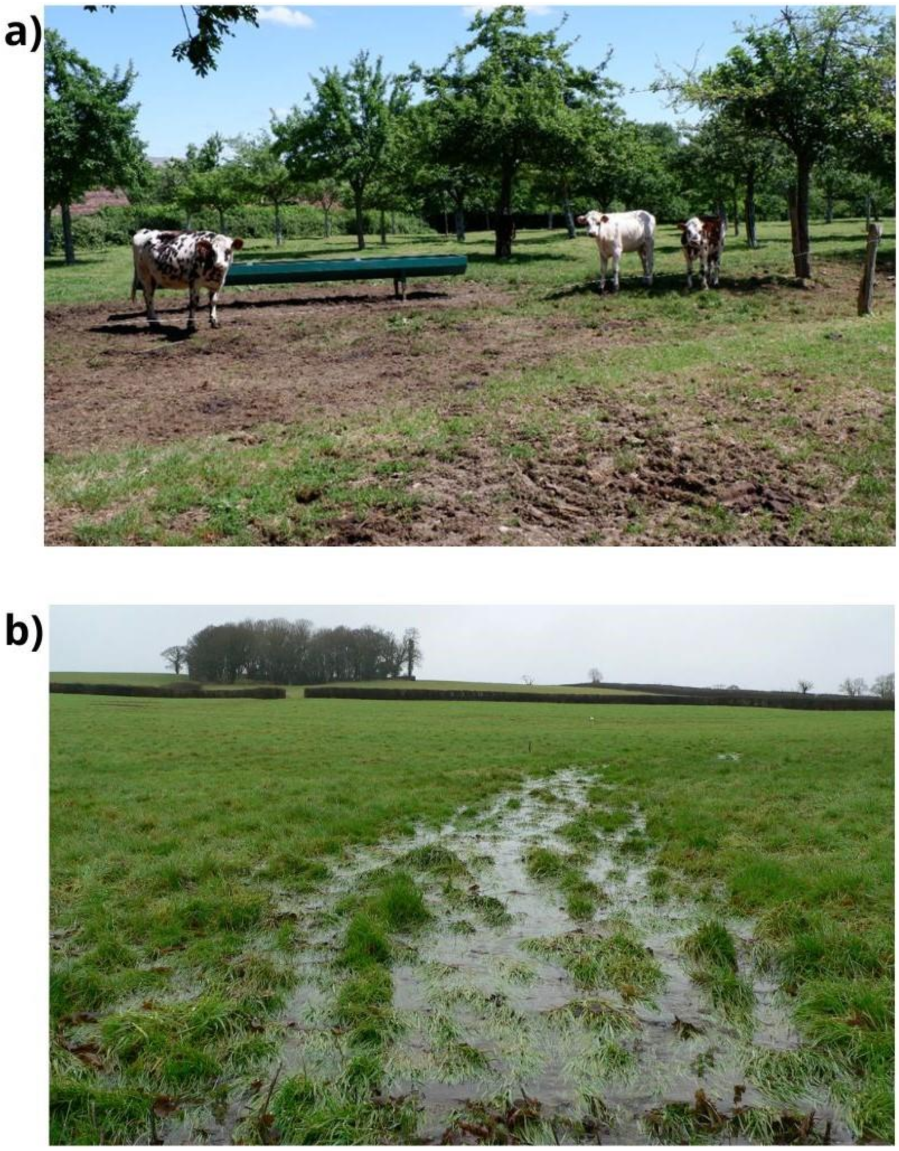

Figure 2. Grassland degradation due to overgrazing and trampling, in a) near to water sources of Northern France (F. Milazzo 2022), in b) in a flat clay soil area of United Kingdom (R. Smith 2023).

4. New grass species for grassland soil resilience

In addition to overgrazing, warmer and drier weather due to climate change is threatening grasslands by reducing grass diversity and productivity. Therefore, future new experiments need to consider new management practices such as grass species resilience [78] not only to ensure productivity but also to preserve grassland soil. Grassland soil quality is strictly related to vegetation health, indeed the reduction of some species may decrease the soil carbon stock [79]. Moreover, in degraded grassland prolonged drought situations with high $CO2$ emissions, can deplete the soil microbial community and promote a shift of the telluric biodiversity, decreasing SOC stock and modifying biochemicals cycles [80], [81]. Furthermore, vegetation cover is a principal factor that influences soil erosion rates

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in grasslands. The capacity to resist erosion greatly depends on the traits of the specific grassland plant community [82]–[84]. Grassland species and varieties differ in their capacity to store water, stabilise soil with their root systems and increase SOM content, all of which are important factors in determining soil erosion rates [85], [86]. As such, the establishment of new species and varieties into grassland communities can be an important technique for mitigating soil erosion. This can be achieved through increasing the functional diversity and species richness of grasslands, or through the development of novel breeds or cultivars with desirable traits, which can then be incorporated into the grassland community. In areas experiencing severe soil erosion or where soil erosion rates are predicted to increase due to climate change and land-use change, for example semi-arid areas of southern Europe [87], establishment of grassland communities that ensure ecological stability, is a key adaptation measure [84]. One way of increasing ecological stability is through promoting or establishing greater plant functional diversity in the grassland community [88]. In many parts of the world, efforts to reduce soil erosion through establishment of new grassland species have not met expectations. Partly to blame for this has been the use of mono-cultures with a simple root structure, which are therefore inefficient at reducing soil erosion compared to areas with greater community functional diversity [89]. It is common practice for species mixtures to be sown or encouraged on permanent grasslands to promote multifunctionality and encourage resilience to environmental stresses including soil erosion [90]. Individual grassland plant traits are an important consideration when choosing species and mixtures that will deliver desired services such as reducing soil erosion. For example, belowground biomass, organic matter contribution by roots and productivity are all important plant traits that can greatly affect the capacity of a grassland system to resist soil erosion due to trampling [82]. A meta-analysis of studies in which plant species diversity was manipulated, found an overall positive effect of increasing plant diversity on belowground biomass, which was considered a key indicator of erosion control [88]. In their investigation of grassland restoration efforts aimed at reducing soil erosion, Zhu et al. [89] showed that communities with a smaller root diameter and greater root tensile strength exerted the greatest control over soil erosion. Medicago sativa is a perennial legume that, as well as being a protein rich forage species, is planted for its ability to protect the soil from wind and water erosion through its deep roots that stabilise soil structure [91]. The incorporation of M. sativa into species-rich grassland mixtures can simultaneously increase forage quality and reduce soil erosion, and as such is an example where multifunctionality can be increased through establishing new species into the grassland community. Novel grassland varieties may extend the depth of sub-soils and range of soil biota by rooting deeper than traditionally used species, which can enhance protection against erosion [90]. Ahmed et al. [92] demonstrated a high genetic diversity of Lolium perenne, the major grass forage species in temperate regions, and stated that this diversity could be exploited to breed new varieties that are adapted to, and can mitigate against, erosion risk. Furthermore, Marshall et al. [93] showed that hybridisation between Trifolium repens and T. ambiguum affected the root structure and density of offspring plants and this could affect soil porosity and consequently impact on erosion rates. Macleod et al., [83] hybridised perennial ryegrass (Lolium perenne) with a more stress-resistant meadow fescue (Festuca pratensis), developing a new cultivar calledxFestulolium loliaceum. Over a two-year experiment, they found that L. perenne 3 F. pratensis reduced surface run-off by 51% compared to the leading English nationally recommended L. perenne species. There have also been promising results from the breeding of grass species with deeper or more extensive root systems e.g. Festulolium (ryegrass x fescue hybrid) which has a greater resource use efficiency (e.g. water), high biomass productivity and high contribution to SOC [94], [95]. Grassland drought resistance is associated with deep-root water uptake [96]. For this reason, Chicory (Cichorium intybus L.), which is a deep-rooted species (>2m), is becoming widespread in temperate and continental climates. In Denmark, Rasmussen et al. [97] compared the subsoil uptaking ability of Cichorium intybus L. with Lolium perenne L. and Medicago lupulina L. , assessing that Chicory benefits better from deep soil moisture (up to 2.3m depth). in

Pennsylvania Skinner [98], introduced the Cichorium intybus L. as a deep-rooted forb, to a pasture mixture composed of orchardgrass (Dactylis glomerata L.), white clover (Trifolium repens L.) and perennial ryegrass (Lolium perenne L.), observing an increment of drought tolerance when chicory constituted more than 24% of pasture composition. Another promising grass species for the semi-arid and Mediterranean climate is the Tedera (Bituminaria bituminosa (L.) C.H. Stirton var. albomarginata). Tedera is an evergreen perennial legume that due to its physiological properties endures high water deficit also in a warm and windy areas [99]–[101]. Moreover, it regrows faster than lucerne after harvesting/grazing, reducing the bare soil condition and yield gap, representing a near-future alternative for the Mediterranean farmer to mitigate climate change effects [102]. Since soil erosion by water is one of the most widespread forms of soil degradation worldwide, the ability of these new varieties to reduce bare soil condition, store greater amounts of soil water and reduce runoff could have significant effects on soil erosion rates.

5. Conclusion

In the context of climate change and increasing grassland degradation, it is essential to understand soil quality development for the resilience of the grassland ecosystems. We show the importance here of using a variety of SQIs, including physical, chemical, and biological indicators, is crucial for achieving different sustainable international goals. Soil quality preservation and maintenance, should be considered essential for environmental quality in general [103]. The application of sustainable management cannot be separated from careful monitoring of soil quality development. Indeed, the assessment of the reviewed SQIs is a reliable strategy for undertaking sustainable and good management practices. However, the efforts to assess soil quality qualitatively and quantitatively are not new, and the standardization of indicators remains an ambitious task. Therefore, due to the site-specific soil quality, the SQIs threshold should be selected according to the base of the soil function of interest. Thus, the development of a SQIs assessment framework, also for limited data availability, can support grassland managers to preserve soil quality. Despite the current limitation of standardization, there are several initiatives aiming to harmonize soil quality information (e.g the Global Soil partnership, the Global Soil Biodiversity Atlas) at a different scale, that can support the management decisions. Sustainable grazing strategies can be implemented and adapted to promote soil quality and the related ecosystem services delivered, with the aim to overcome climate change effects. The test of new grassland species, drought-resistant and with desirable traits for soil protection, must be explored for the different bioregions aiming to improve grassland resilience in terms of soil protection, production, and ecosystem services delivery.

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