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Women in Soil Science

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Women in Soil Science

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The Spanish Journal of Soil Science is proud to offer this platform to celebrate the achievements of women in the field of soil science and hopefully inspire the next generation of female soil scientists.

Led by Dr. Andrea Vidal, Dr. Michele Francis and Prof. Rosa Maria Poch, this Special Issue highlights the latest research from women in the soil science field from across the globe.

At present, less than 30% of researchers worldwide are women. Long-standing biases and gender stereotypes are discouraging girls and women away from science-related fields, and STEM research in particular. Science and gender equality are, however, essential to ensure sustainable development as highlighted by UNESCO.

The work presented here highlights the diversity of research performed across the entire breadth of soil science led by women, and presents advances in theory, experiment and methodology with applications to compelling problems. It also welcomes more sociology-oriented papers, analyzing the role of women researchers in soil science, as well as those dealing with women as the main actors of soil management in various regions of the world.

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Editorial: Women in Soil Science

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Editorial on the Special Issue

Women in Soil Science

Welcome to this special edition of *Women in Soil Science*. The Spanish Journal of Soil Science is proud to offer this platform to celebrate the achievements of women in the field of Soil Science and hopefully inspire the next generation of female soil scientists.

Led by Dr. Andrea Vidal, Dr. Michele Francis and Prof. Rosa Maria Poch, this Special Issue highlights the latest research from women in the Soil Science field from across the globe.

At present, less than 30% of researchers worldwide are women. For example, in the US women represent only 24% of the soil scientists in academic faculty positions. Long-standing biases and gender stereotypes are discouraging girls and women away from science-related fields, and STEM research in particular. It is essential for both the progress of the field and the fulfilment of the UN Sustainable Development Goals (SDG) to change traditional mindsets and promote gender equality within the Soil Science field, as well as science more broadly.

In this edition, we celebrate the women working in the wider field of Soil Science and we recognise their struggles to become scientists, especially in countries where the playing field is not level. Without an early education focused on strong reading and mathematical skills, a scientific career cannot follow.

The eight papers presented here highlight the diversity of research performed across the entire breadth of Soil Science led by women. Four of the papers deal explicitly with the issue of gender in soil science, either from historical or geographical perspectives, giving visibility to women soil scientists whose contribution to Soil Science has not been given the recognition it merits. The remaining four papers illustrate soil research carried out or led by women in Mexico, Spain, Canada and Brazil showing excellence in science regardless of the authors' gender.

Díaz-Raviña and Caruncho are the authors of the interesting review: "*A brief analysis of the contribution of women to Soil Science.*" They present data on female soil scientist ratios in several countries from a time perspective, along with the socioeconomic and political reasons for their evolution. They explain what makes research led by women necessary for the advance of soil science and give reasons for its promotion from the early school years. Special attention is given to Russian and former soviet female soil scientists. Gerasimova's contribution entitled "*Maria Glazovskaya -A pioneer soil scientist and geochemist ahead of her time (1912–2016)*" gives an account of one of these "forgotten" Russian soil scientists, who made essential contributions to the knowledge of the world soils and of soil geochemistry, establishing the bases for quantitative soil classification and putting forward some concepts considered hot issues today such as soil carbon pools and emissions; and environmental time bombs applied to soil pollution.

The paper "*Reevaluating diversity and the history of Women in soil sciences: a necessary step for a real change*" (Reyes-Sánchez and Irazoque) deals with the implications of low diversity in the sciences. This review highlights how increasing diversity benefits the field in general. The authors present valuable data on historical discrimination of indigenous peoples and knowledge in Soil

Science, female versus male participation in science programs and societies, inclusion statistics in the field of Soil Science, and the history of several notable women in geology, earth science, and soil science.

"*Gender equality in soil science in Italy: wishful thinking or reality?*" (Adamo et al.) analyses the role of women in the Soil Science field in Italy. Soil Science has been a traditionally male-dominated area of study. Although there is still a strong male-female bias, the results show that women are increasingly more present in high-responsibility positions in Italian research institutions. Also, the authors highlight that, when scientific production is evaluated, no difference appears between women and men at all career levels. Therefore, despite the favourable trend, gender equality has not been achieved yet in Italy in this field of study. Better investment, improved public resources and political changes are needed to achieve a more gender-balanced reality.

González-Vargas and Gutiérrez-Castorena in their paper "*Brightness values-based discriminant functions for classification of degrees of organic matter decomposition in soil thin sections*" used image processing to classify *in situ* organic matter at different stages of decomposition. The decomposition of soil organic matter is a complex process due to its diffuse nature, and understanding it is fundamental to understanding carbon dynamics. Using images of *in situ* organic matter in soil thin sections, they created classification models using linear discriminant analysis, considerably reducing the volumes of information for data processing. The results will help researchers to quantify soil organic matter decomposition which is fundamental in understanding the dynamics of *in situ* carbon in the soil.

The paper "*Changes in soil phosphorus pools in long-term wheat-based rotations in Saskatchewan, Canada with and without phosphorus fertilization*" (Cade-Menun) reports on soil P and crop yield dynamics as a function of field and crop management. The study is from an unusually long experimental period in a long-term rotation study in Swift Current, SK Canada. There are only a handful of studies like this across North America, and there are even fewer studies that include long-term soil P data. The results are of great relevance for fertilisation planning for good crop yields that are compatible with the protection of aquatic media.

Marques et al. in their paper "*Land recovery and soil management with agroforestry systems*" analysed experiences and studies from different countries in tropical areas. They compiled information from secondary sources about the implementation of agroforestry and its benefits to the soil. The data show that the main problems related to soil degradation in these areas are soil erosion and decreased soil fertility. The authors conclude that the adoption of agroforestry systems improves many aspects of soil quality, which reaffirms agroforestry as a sustainable alternative for conventional agricultural systems to achieve the UN Millenium Development Goals (MDGs). However, more research and quantitative data are needed to be able to widely recommend agroforestry, with specific selection and management of species, in different regions, climates and soils.

Álvarez et al. in "*Quantification of gypsum in soils: Methodological proposal*" apply different field and laboratory methods to measure gypsum contents in a soil from the Ebro valley and discuss their validity and feasibility. Their findings allow the authors to propose a methodological path to quantify gypsum in soils, taking into account field observations, which has relevance in e.g., soil classification and land evaluation.

The editors would like to thank the contributors and reviewers, without whom this Special Edition would not have been possible. It provided a unique opportunity to highlight the role of women in Soil Sciences, both historically and in the present. It has revealed both how far we have come, despite the difficulties, and how far we still need to go. To achieve gender equality, an honest commitment from institutions and funding agencies is needed. We also would like to point out that besides the gender imbalance, there is a funding imbalance between developed and developing countries that needs to be tackled. Soil Science is a multifaceted discipline that needs a multifaceted and diverse group of minds to solve the next generation of questions.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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REVIEW
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A Brief Analysis of the Contribution of Women to Soil Science

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Soil science has traditionally been dominated by men, and women remain a minority in this field today. Despite soil science being more recent than other scientific disciplines, many women have made significant contributions to the field, although these are not generally recognized. Recent studies have shown a lack of gender balance and low levels of diversity and inclusion in soil science in several countries worldwide. Although partial and fragmentary, the information provided by the present study of the involvement of women in soil science research reinforces the idea that science should be looked at from a gender perspective in order to promote real equality between men and women. Science and soil science are both the result of historical and cultural events and social context. Science is not neutral: it is social and gendered and always will be, but we can try to make it more inclusive.

Keywords: reflections on gender perspective, scientific knowledge, women soil scientists worlwide, Russian and Soviet female scientists, foreign female soil scientists

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INTRODUCTION

According to UNESCO (2021a; 2021b), men and women must enjoy equal opportunities, power, choices, capabilities and knowledge. Girls and women account for 50% of the world's population and hence 50% of its potential. Gender equality is not only one of the fundamental rights of our society, but it is also one of the fundamental pillars on which to build a peaceful, prosperous and sustainable world. UNESCO's International Women's Day (8 March) highlights actions that encourage gender parity and commemorate the social, cultural, economic and political accomplishments of women worldwide.

For more than 75 years, gender equality has aroused great interest in society. The United Nation's Commission on the Status of Women (CSW) addresses this issue, leading debates on discrimination against women and girls around the world and promoting numerous actions to promote their rights. Regarding the field of science, the NU's resolution of 14 March 2011 and 20 December 2013 recognize that equal access to and participation in education, training and science and technology are imperative in order to achieve gender equality and women's empowerment. In order to draw attention to this issue, in 2015 the United Nations proclaimed 11 February as the International Day of Women and Girls in Science. However, despite the efforts made throughout the years, studies show that full, equitable access and participation of women in science is far from being achieved (Markert, 1996; CSIC, 2021). The inequality is particularly marked in the so-called STEM careers (Fox, 1994; NU, 2020; CSIC, 2021; Davila dos Santos et al., 2022), i.e., those related to science, technology, engineering and mathematics, and occurs both in less developed countries and more developed countries such as European Union countries and the United States.

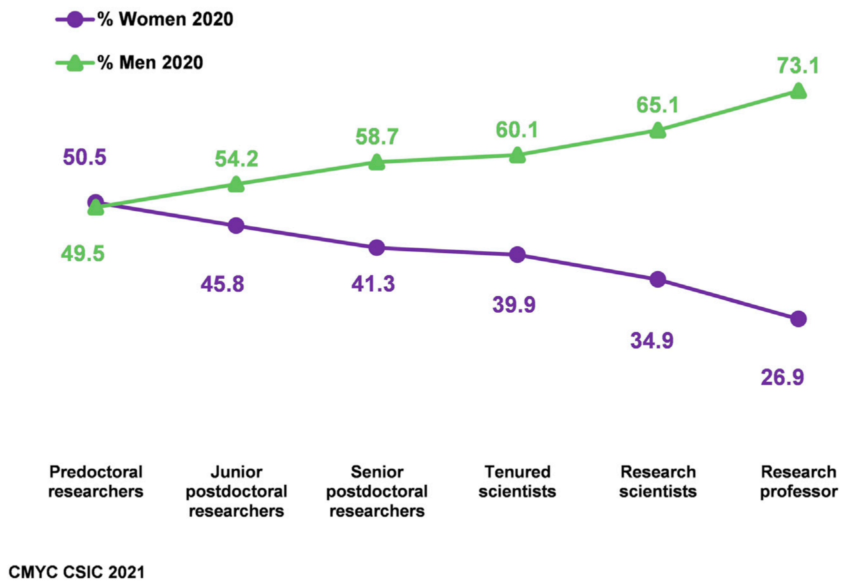

FIGURE 1 | Distribution of the research staff of the Spanish Research Council by gender in 2020 (CSIC, 2021).

Despite the growing demand for data on the involvement of women in science in different countries, to enable statistical analysis and for use in policymaking, information on this topic is scarce. The UNESCO Institute for Statistics (UIS) recently published a report (FS/2020/SCI/60: NU, 2020) including data on research and experimental development and a map depicting the world gender gap in science. In 2017, the average proportion of women scientists worldwide was 30% (range 23%–49%). The proportions were lowest in West and South Asia and the Pacific (23%–25%), followed by sub-Saharan Africa, Western Europe and North America (31–33%) and Eastern and Central Europe and the Arab States (39%–41%), and highest in Central Asia, the Caribbean and Latin America (46–49%). The proportions varied widely in different countries, ranging from 29% (Peru) to 61% (Venezuela) in South America, from 26% (Netherlands) to 53% (North Macedonia) in Europe, from 4% (Chad) to 56% (Tunisia) in Africa, from 8% (Nepal) to 77% (Myanmar) in Asia, and finally from 33% (New Zealand) to 52% (Papua New Guinea) in the Pacific region. Studies concerning changes in the contribution of women to different scientific disciplines at the national level are therefore necessary to identify trends and take actions to achieve a gender balance.

In order to examine the contribution of women in science in Spain, we used data provided by the Spanish National Research Council (CSIC) for the period 2000–2021 (CSIC, 2021). The research carried out in this public research institution, which includes 120 institutes distributed throughout the country, is multidisciplinary and multisectorial, covering all areas of knowledge, organised around three global areas: Society, Life and Material. The CSIC, sensitive to the problem of the relatively low number of women involved in the scientific work of the Institution, created the Women and Science Commission (CMyC) in 2002, with two main objectives: to study the possible causes that hinder both the entry and advancement of women and to propose possible actions aimed at achieving equality between men and women in the CSIC. The annual reports of women researchers prepared by the CMyC are available on the CSIC website.

The results of the report on Women Researchers 2021 (CSIC, 2021) indicated that there are almost no differences between the proportions of men (50.5%) and women (49.5%) undertaking pre-doctoral research (**Figure 1**). However, when the researchers advance in their career through the higher categories, these differences are markedly accentuated (27% and 73% for women and men, respectively). Comparison of scientific careers between 2009 and 2019 reveals that we are moving away from the desired equality (**Figure 2**). Women find it difficult to advance in the research field, as in the last 10 years there has been an increase of only 4 percentage points in the proportions of women in highest categories (from 23% to 27%), partly due to a greater number of retired male researcher lecturers. Women are also promoted less often, remaining in the same category for longer and receiving lower salaries. In the period considered, the proportion of female research staff was 36.2%, while women represented 23% of the staff participating in management of research centres: these values are within the range reported by the UN (UN, 2020). As expected, the presence of women leaders improves the visibility of the scientific achievements of women researchers. When appointed by the CSIC as President in 2017, Rosa Menéndez López became the first female President of this Spanish research institution in the 78 years of its existence. In 2019, López organized an event in recognition of the work of the pioneering scientific women employed by the CSIC (250 women) who have remained anonymous for so long and who have played a very important role in the advancement of scientific knowledge. Recently, in June 2022, Eloísa del Pino Matute became the second female President of the CSIC.

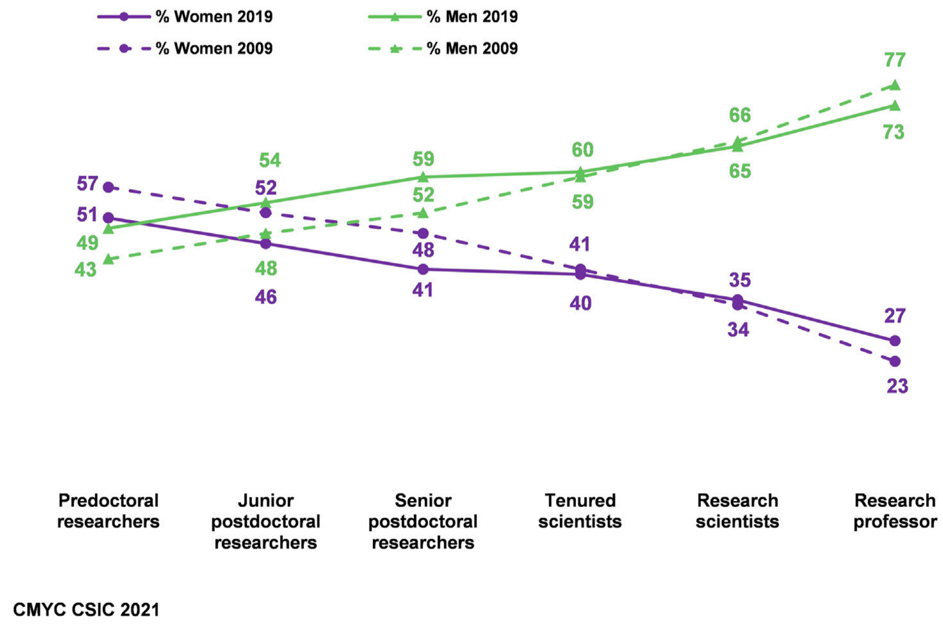

FIGURE 2 | Distribution of the research staff of the Spanish Research Council by gender in 2009 and 2019 (CSIC, 2021).

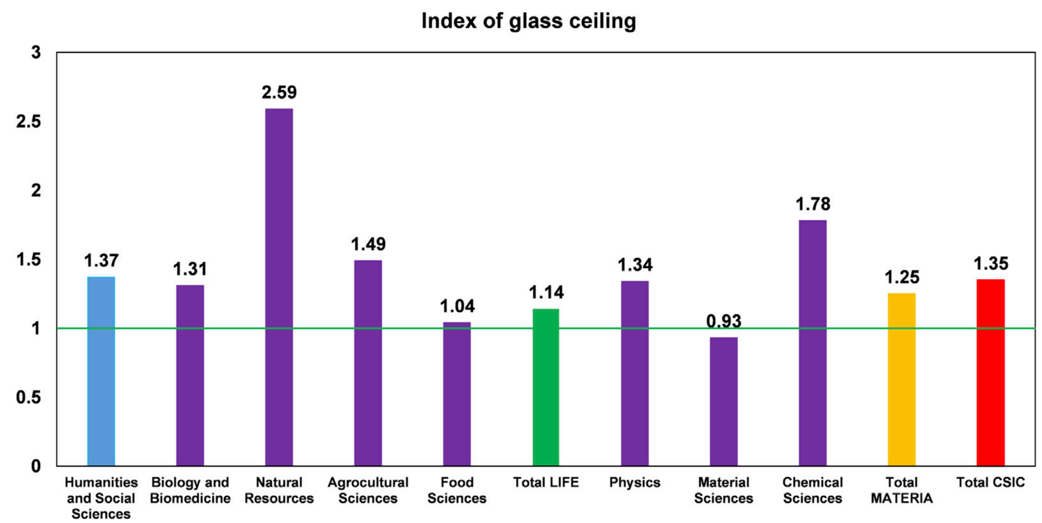

FIGURE 3 | Glass ceiling index of the female scientists of the Spanish Research Council during the period 2000–2020 (CSIC, 2021).

The analysis, disaggregated by gender into social, life and material categories, revealed that gender balance is not reached in any of the categories: Society, 38.8%; Life, 36.8%; and Material, 34.7%. In 2021, the global mean value of the glass ceiling index (GCI) remained at the same value as in the previous year (1.35), breaking the downward trend experienced over the previous 15 years (**Figure 3**). However, the GCI for the sub-area of Natural Resources (2.59) is of particular concern, as rather than decreasing relative to previous years, it has actually increased at a very alarming rate. In the other the sub-areas, the GCI values are similar to those in previous years, with a value of less than one for the Material Sciences and Technologies subarea. Analysis of these reports on Women in Science (2002–2020) (**Figure 4**) clearly demonstrates that the passage of time is in itself not sufficient to achieve changes and that, at least in Spain, active policies are required to promote gender equality in science. It is worthy of note that in Australia the implementation of gender equity strategies encompassing numerous measures of legislation and action plans of the government and university institutions and the individual faith

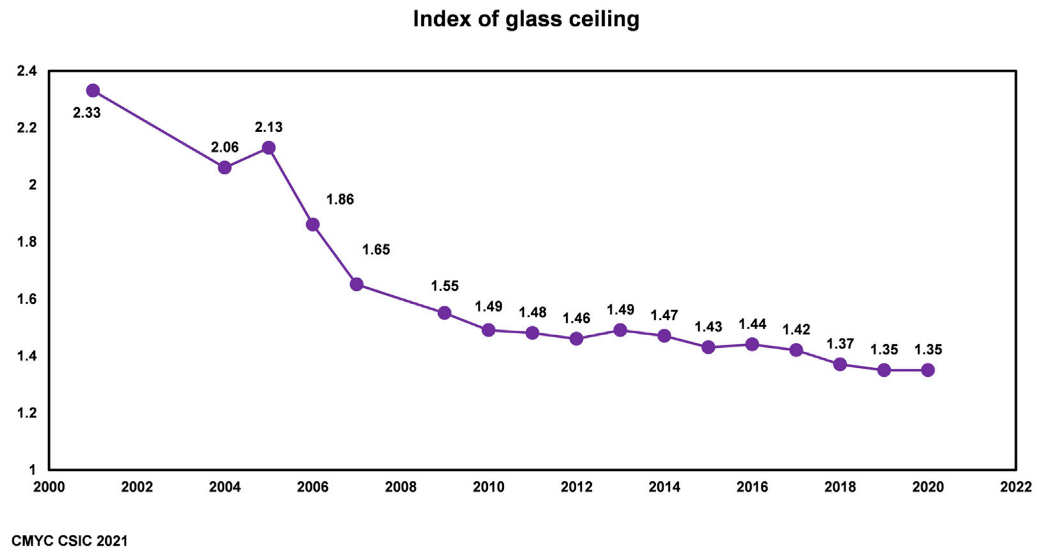

FIGURE 4 | Glass ceiling index of the female scientists of the Spanish Research Council distributed by subareas within the three global areas of society, life and material in 2020 (CSIC, 2021).

of researches have been very effective (Winchester et al., 2006). In the early 1990s, women researchers represented 20% of the teaching and scientific staff, occupying only 6% of the positions of greatest responsibility. Two decades later, the situation in the workplace has changed remarkably given that women now represent 44% of the research and teaching staff and occupy about 31% of the positions of greatest responsibility.

To address the subject of gender equality in science, the work involved in scientific professions must first be defined. Researchers participate in and carry out activities to generate new knowledge in all scientific fields (both natural and social sciences). According to Pérez Tamayo (2009), science is a creative activity aimed at understanding nature and that generates knowledge through a scientific method based on a deductive approach and that aspires to achieve consensus among technically trained individuals. The scientific method includes the following steps: 1) definition of the problem to investigate, 2) establishment of a hypothesis to explain the problem, 3) testing the hypothesis by conducting experiments 4) analysis of the data and drawing a conclusion confirming or reflecting the initial hypothesis (if the latter is the case or the data are not clear a new hypothesis must be elaborated) and f) presenting the findings to others. The conclusions usually lead to new questions that will be pursued, thus enabling advancements in knowledge to be made. Thus, the most important traits of a good researcher are consistent curiosity, open-mindedness, enthusiasm, intelligence, determinedness and good personal and communication skills (Markert, 1996). As these personality traits do not depend on gender, it is theoretically possible to achieve gender equality in all scientific disciplines across the world.

When reflecting on the five steps of the scientific method outlined above, we can conclude that the knowledge obtained through the use of this method should be exempt from any gender bias and, in general, from any factor concerning social order, i.e., scientific knowledge should remain outside of ideology, economics, political interests, etc. However, this seems to contradict the imbalance between the number of male and female scientists, which has been evident (at least since the middle of the 20th century) to institutions (universities, research centres and the scientific community) and to citizens concerned about issues such as equality.

In order to investigate whether scientific knowledge is neutral and universal and remains outside any question of social order, we conducted an analysis of the scientific world from a gender perspective. We first examined how feminist theories, supported by the contributions of philosophers of science in the 1960s and 1970s, incluing Kuhn (1962) and Lakatos (1978), dared to denounce the gender bias that affects the world of science. These philosophers denounced not only the unequal number of male and female scientists, but also other issues such as 1) the biases in scientific research when women are the object of study, 2) the glass ceiling, which is closely linked to the problem of conciliation of family life and work life and 3) the higher prevalence of women in professions in the humanistic field in contrast to the clearly masculinized profile of scientific-technological studies.

After reflecting on the gender perspective in science, we used an example to illustrate the ideas stated. Soil science, the scientific discipline of one of the authors of this work, was selected as the example and hence as the objective of our research. An initial examination led us to focus on a data-based denouncement of the unequal number of men and women dedicated to this area of knowledge. We used the CSIC database to address the situation in Spain, and we used the data on some other countries, included in the scarce published papers to which we had access, for the rest of world.

REFLECTIONS ON GENDER PERSPECTIVE IN SCIENCE

The model of male dominance in the history of humanity is widely recognized nowadays and androcentrism is considered a socio-cultural paradigm. However, this paradigm has not been widely recognized within the framework of science, and the androcentric point of view is not taken into account in relation to the social context or human nature.

The pattern of male dominance has been so widespread that human studies have often only included men as subjects, and innumerable studies have been conducted from the male point of view. Thus, scientific studies of women have primarily been conducted to demonstrate and highlight, with a notably biased viewpoint, the differences—both real and assumed—separating men and women, especially in regard to reproduction and thus "reducing women to their reproductive anatomy" (Maffi, 2016). This approach entails several gender biases, including the following: 1) The choice of study topic. The critical importance of what has been called "funding agencies" that are not very interested in the involvement of women in science (either as researchers or as research subjects) is demonstrated. Although there are many reasons for this lack of interest, most are related to the economy/power axis. 2) Negation of the power relations between genders. In addition to the androcentric vision, which identifies masculine categories with human beings, denying gender and sexual diversity, the power element situates men on a higher plane to which women cannot aspire. 3) The techniques of observation and data analysis (i.e., selecting what is significant and what should be discarded in research) determines the process and the final product. In this respect, increasing the number of variables and conducting analyses of co-variance can minimize reductionist gender biases.

In the androcentric and patriarchal world, science cannot escape from these sources of bias. Demonstrating bias is an important task, although women scientists will usually continue to conduct the science that social conditioning allows. The commitment to gender perspective in science includes the task of unearthing, identifying, making visible, and valuing the number, names and biographies of women scientists, as well as the milestones they have reached, the academic and administrative roles they have occupied and the texts they have written and/or published. This arduous task forces us to reconstruct, in form and content, the history of scientific thought to include this new perspective, a feminist and multidimensional point of view that requires a change in the positivism paradigm. The point is not to add women's names and bodies to the hegemonic normative model: it is to rethink scientific study as social and thereby evaluative, as a product of social interactions between members of a community and their interaction with other objects and subjects involved.

The task of reconstruction began in the 1960s with Kuhn's proposal, outlined in the publication "The structure of scientific revolution" (1962) and later supported by the studies of Hanson (1976), Lakatos (1978) and Feyerabend (2015). These philosophers tried to understand science by highlighting the social component, which changed the traditional concept of scientific knowledge based on logical reasoning applied to data obtained by observation and experimentation using a neutral and context-independent methodology. This led Longino (1979) and Fox Keller (1985), experts in the philosophy of science, to reflect on the biases that gender imparts to scientific knowledge, showing that the idea of scientific study as objective, positivist, rational and formal is a social construct that corresponded to all of the qualities highly valued by and attributed to man. The male gender was identified as rational, objective and positive, while women were characterized as weak, subjective and irrationally emotional. The feminist critique demanded that the category of gender became a fundamental element for understanding and reconstructing the history of science (Harding, 1996). This implies the use of the analytical category of gender and its double dimension proposed by Scott and Amelang (1990), indicating, on the one hand, gender as a constitutive element of social relationships based on the differences between sexes, and, on the other hand, as a primary form of power. Both of these aspects of gender are interdependent in our socio-cultural model and imply considering gender a social, cultural, political and historical construction that encompasses the characteristics that are assigned to people on the basis of their biological sex and that have traditionally placed men in a privileged position and women in situations of political and social exclusion.

From this feminist perspective, in the last 4 decades, significant issues that were previously considered the status quo have been objectively described, including the following examples: the absence of women in science; women's lack of interest in science; the particular natural link between women and the private space, motherhood and care; women's lack of professional ambition; and the existence of exceptional women, often considered freaks, eccentric or degenerate, who have achieved prestige in the world of science. Although the limited space prevents us from considering many other issues, the above examples are considered in more detail below.

1) The late incorporation of women into academia. The late access of women to higher education where one acquires the capacities and abilities to carry out scientific studies is unquestionable. In Spain, free access to higher education did not become available until the in 1910, and the first female University Professor was appointed in 1916. However, true integration in higher education, including specialized training that allows real access to scientific tools, doctoral programmes, master's degrees, etc., did not take place until the 1960s. The importance of this in terms of cause/effect is generally recognized to explain the lack of a solid tradition of women in science in Spain. Nevertheless, the exclusion of rights is also due to the socio-cultural androcentrism that conceived women as inferior beings with a lower capacity to learn, and for centuries male philosophers and scientist created diverse and peculiar arguments to confirm this idea (Maffi, 2016).
2) The deliberate silencing of women's work. Although the presence of women in the world of science has been considerably less than that of men, the data were exaggerated by the names of female scientists being

deliberately hidden or omitted (Guil, 2016). There are more women scientists than are generally named and recognized. In fact, in many cases the important contributions of women to the advancement of scientific and technical knowledge have not been properly recognized (Solsona, 1997; González and Sendeño, 2002). In this sense, science has not been so "alien" to the proclamation, management and justification of the "prejudices" that undervalue feminine nature.

3) The proclamation and dissemination of the masculine nature of science. Science is usually linked to masculinity based on the traditional concept of science as rational, formal and objective, but also because the scientific texts and biographies used in teaching at academic and institutional levels are predominantly written by or are about men. From childhood, boys are pushed towards and motivated by the knowledge and importance of STEM careers: any learning difficulties they have are presented as a challenge accompanied by the consideration that whoever dominates the world of science is an intelligent man who participate in making decisions of great social transcendence, and their prestige in society becomes exemplary. The typical image of a scientist is as a crazy man locked in his laboratory, distancing himself from the people around him with a normal daily life. By contrast, women are typically characterized by their particular abilities in contextualized knowledge; their skills in mastery of language are exalted, along with their ability to empathize and their natural ability to care and to deal with education. All this is reflected when girls choose what to study and/or which professions to pursue. Thus, although in Spain about 50% of university students are women, only 20–30% choose to study careers in scientific or scientific-technological careers, while the remaining 70% choose careers in the field of teaching, health and social sciences (Agudo, 2003).
4) The idea of exceptional and/or the degenerate. Women who love and work in science are not rare birds, nor are they necessarily endowed with exceptional abilities that allow them to do something not accessible to other women. Nor are they degenerate beings who break with their nature by cross-dressing as males and adopting male practices and presuppositions. There are many women who are scientists, and many are both scientific professionals and mothers: they are women because of their biological condition and their social commitment to their gender, and they are scientists because they opted to train seriously in their chosen fields to generate knowledge.
5) The brake on women's professional ambitions, which are often considered to limit the development of personal life. The limited access to the highest positions and degrees is linked to the late and partial incorporation of women in science. However, the glass ceiling often also emerges from a "voluntary" renunciation by women of their legitimate aspirations of professional power or work-related ambitions. They do this, as they understand that advancing their careers is an obstacle to the development of their personal lives, fundamentally related to the tasks of caring for others in the family setting (children, elderly, dependents). This dilemma is crucial in relation to motherhood (Aguinaga, 2004), and family conciliation policies must be implemented and men and women must be involved in care on an equal basis, given that we can all do this and all of us at some point in our lives need to be cared for (Camps, 2021).

Identifying the traits that are determined by gender requires recognition of several variables, including gender but also social class and race, among others, which have determined a large part of the categories, classifications and descriptions through which we know and describe the not only human world but also the physical world. The new viewpoint is committed to showing how scientists study subjects within specific social contexts. Scientists are not abstract subjects endowed with universal faculties; they are privileged members of society who build images and explanations of nature that reinforce their hegemonic position in the world. Thus, since the 1970s, feminist critics have striven to denounce normative science as an activity that reproduces and/or legitimizes discrimination against women, which is supported by the activity of philosophers of science, led by Kuhn in the 1960s and 1970s. With this impulse, the feminists of the second wave (which in the 1970s and 1980s are consolidated in the academic world) have focused on returning to the essence of science itself, reclaiming its hypothetical character, which had been so subtly forgotten by those who created and used it (Agudo, 2003). The gender/science system (Fox Keller, 1985) was established and the new scientific epistemology of women's studies emerged, first in the Anglo-Saxon world and by direct influence throughout Europe, including Spain. These studies are framed within feminism and, as indicated by Flores (2013) "what characterizes feminist research compared to other non-feminist research is its political commitment and activism in order to improve the situation of women and other marginal groups. It is contextual, socially relevant, inclusive and takes into account the role of experience and subjectivity in research. This research is guided by different methodological approaches and theoretical paradigms that conform to the feminist principles of emancipation and social change." Such studies and research have increased enormously over the last decades, addressing different options and conceptualizations and proposing constructive alternatives aimed at defending this new model of scientific knowledge. This is an essential tool for science informed by a moral and emancipatory policy with participative, antiracist, anticlassist and antisexist values, despite being immersed in an "occidental, bourgeois and masculine framework" (Harding, 1996). The new epistemology of science with a gender perspective recognizes that extracting androcentric values from science will not make it neutral and objective, but it will get rid of coercive and discriminatory values. Science with a non-sexist gender perspective must assume the impossibility of objective science/research, as it can never be exempt from social values and interests. In summary, the idea is that good science is not that which is value-free, but rather that which incorporates good values.

WOMEN IN SOIL SCIENCE

Soil is a natural, non-renewable resource that takes a long time to develop, but which can be quickly destroyed or degraded. Soil hosts a quarter of our planet's biodiversity and provides ecosystem services needed for the correct functioning of natural systems (such as supplying nutritious food, clean drinking water and raw materials, and carbon sequestration) and which are essential for overcoming societal challenges like climate change, food security, biodiversity loss and the safeguarding of human health (Montarella and Panagos, 2021). In 2015, the UN established the sustainable development goals (SDGs) promoting awareness and citizen responsibility regarding the importance of soil and its protection. Soil health is enhanced by promoting its sustainable management in order to achieve the following SDGs: 1 (End poverty), 2 (Zero hunger), 3 (Good health and well-being), 5 (Gender equality), 6 (Clean water and sanitation), 7 (Clean and affordable energy), 9 (Resilient infrastructure, inclusive, sustainable industries, and innovation), 11 (Sustainable cities and communities), 12 (Production and responsible consumption), 13 (Climate action) and 15 (Life on land) (Lal et al., 2021). These goals are also associated with the European Green Deal, approved in 2020, which includes a set of initiatives whose overall objective is to achieve climate neutrality in the EU. However, in most developing countries, less than 1% of the GDP is invested in research related to the study and knowledge of soil, at both regional and national scales. The scientific community of soil scientists is currently actively discussing gender equality given the inequality and low diversity and inclusion of women relative to other subdisciplines within the earth, natural and agricultural sciences (Brevik, 2019; Vaughan et al., 2019; Carter et al., 2021; Dawson et al., 2021). Female and male soil scientists around the world must have equal opportunities to contribute their knowledge and experience towards the sustainable management of soils and hence to achieve sustainable development goals. Research and education centres must train young male and female soil scientists who will have the ability to approach and solve problems related to soil productivity and ecosystem services.

Many women have made important contributions to the advancement of knowledge in soil science but are unknown, even within the field itself. Women role models are needed to maintain soil health and promote scientific vocations in soil science in order to reduce gender discrimination in this field. We used the list of Honorary Members of National Soil Science Societies (in this case, the Spanish Society of Soil Science, SECS) and International Union of Soil Science (IUSS) as databases in order to find the names of such women. The IUSS, founded on 19th May 1924 as the International Society of Soil Science, is the global union of soil scientists. It currently has 60,000 scientists around the world, of which 134 are honorary members (130 men and 4 women). Maria Mikhaylovna Kononova was the first women to became an Honorary Member of the IUSS (1974, USSR) and was then followed by Maria Gerasimova (2016, Russia), Mary Beth Kirkham (2016, United States) and Rosa M. Poch Claret (2020, Spain). The alarming, significant gender inequity among honorary members (3% women versus 97% men) clearly shows that women's contribution to soil science during an entire century has not been recognized, i.e. since the development of this science in the late 19th century. Surprisingly, 75% of women have been included in the list of honorary members in the last 4 years. During the period 1924–2016, women accounted for only 1.05% of the total (94 men versus 1 woman), whereas the percentage increased notably during the period 2016–2020, reaching a value of 12.5% (21 men versus 3 women). Likewise, women are also under-represented in Presidential and executive Committees, Divisions, Commissions and Working Groups of the IUSS (20–37% in 2022). When appointed by IUSS president in 2019, Laura Bertha Reyes Sánchez became the first female president in the history of IUSS (95 years).

The Spanish Society of Soil Science (SECS), founded in 1957, has 564 members (325 men and 239 women). The proportion of women (42%) is higher than that observed by Dawson et al. (2021) for 44 national soil science societies worldwide (32%). The SECS has 14 honorary members (11 men and 3 women). Tarsy Carballas Fernández was the first female honorary member (2011, Spain), followed by Laura Bertha Reyes Sánchez (2020, México) and Montserrat Díaz Raviña (2022, Spain), respectively. As in the IUSS, most female honorary members have been included in the last 4 years (67%) and greater inequality was observed for honorary members than for the total number o f members (21% versus 42%). The data demonstrate that the presence of women in leadership positions in the ISSS and SECS remains very low and that urgent actions towards greater inclusion and gender diversity should be implemented. Therefore, there is an urgent need for female soil scientist role models to help give visibility to the soil and promote scientific vocations in this field. In this sense, we consider that the honorary members of the national societies of soil science worldwide should be viewed by others as successful soil scientists. The photographs of the mentioned female honorary members of IUSS and SECS are shown in **Figure 5**.

Collection and analysis of information concerning the lives and achievements of women in soil science is of great interest both for gender studies and for promoting scientific vocations. Nowadays, the internet can be used as an information search tool, and many investigators are taking advantage of the potential of internet-based searches to provide large amounts of worldwide data to assist their studies. However, since the birth of the internet in the 1980s, this channel of information in electronic format has shown some limitations when used for studies of the history of the development of soil science. Therefore, for information on topics prior to this date, printed documents that are not available on the internet will probably also have to be used.

Finding written sources of documentation can be time-consuming and expensive. In addition, there may be difficulties associated with our level of knowledge of the different languages in which the documents are written. In

FIGURE 5 | Laura Berha Reyes Fernández, Maria M. Kononova, Maria Gerasimova, Mary Beth Kirkham, Tarsy Carballas Fernández, Montserrat Díaz Raviña and Rosa M. Poch Claret. The photograph of M.M. Kononova, which is a courtesy of Elena Rusakova (Deputy Director of the Museum), is in the Archive of the Dokuchaev Central Soil Science Museum. F.3. Op.1. D.55. L.8.

this respect, information is available on internet about all of the female honorary members of the soil science societies mentioned above, except Maria Mikhaylovna Kononova (1898–1978). This is surprising as Kononova is the author of "Soil organic matter: its nature, its role in soil formation and in soil fertility" (1963), which is still considered the reference book for specialist in soil organic matter worlwide. The book is available in print version in Russian, Polish, Chinese, German, Japanese, English and Spanish, and it includes around 1,000 references. Kononova acted as chief editor and/or member of the editorial board of the journals "Soil Science" and "Geoderma" and actively participated in the "International Symposium Humus et Planta", which was held in Prague (Czech Republic) during a period of 14 years. Of her private life, it is only known that she had a daughter and a grandson (Pavel Krasilnikov, personal communication). Due to the lack of biographical details and information about her scientific achievements, we asked P. Krasilnikov (a soil researcher at Karelia Research Center RAS, Petrozavodsk, Russia and an honorary member of the IUSS) for assistance. He sent us a book written in Russian by Svetlana Arsenievna Sycheva on the role of Russian women in soil science (Sycheva, 2003). Reading this interesting monograph, made us realize that the contribution of Russian and Soviet women to soil science is probably greater than that of women scientists from other countries (345 women soil scientists, including M.M. Kononova), owing to political, socioeconomic, cultural and geographic circumstances.

CONTRIBUTION OF RUSSIAN AND SOVIET WOMEN TO SOIL SCIENCE

The history of Russian soil science is closely associated with Vasily Vasilyevech Dockuchaev, widely regarded as the father of soil science, and his colleagues and followers. At first, women worked together with these researchers as laboratory assistants, secretaries, technicians and engineers. Women then became researchers and many of them developed new lines of investigation. Women's contribution to soil science in Russia and the Union of Soviet Socialist Republics (USSR) is immense and diverse. In the 1930s, women represented 30% of researchers; however, their scientific achievements have not been widely recognized, and in fact, publications on the history of soil science in Russia and the Soviet Union only included men. However, as mentioned above, a comprehensive reference book on the contribution of women to the various soil science disciplines in Russia over the last century was written at the beginning of the century (Sycheva, 2003). This 244-page book includes information on 345 women soil scientists, regarding both their careers (research lines, scientific accomplishment most relevant publications) and biographical details directly related to their scientific careers (dates of birth and death, family members, studies and teachers, dates when doctoral theses defended, activities related to teaching and management and distinctions in recognition of their work). Although the book is written in Russian, we found brief summaries of the content written in

English by Sycheva (2006) and Prikhod´ko (2006), and we translated the book from Russian to English using a Google application.

For centuries Russia was a nation with a largely rural population subjected to an absolutist monarchical regime. The situation of poverty, the devastating effects of the First World War and the economic and social crisis led to a situation of famine that caused the Russian revolution at the beginning of the 19th century (1917). The autocratic regime was overthrown and a new model of the Leninist state was gradually built, i.e. communist Russia, which later gave rise to the creation of the Union of Soviet Socialist Republics. In this social democratic regime, there were great cultural changes that included improvements in the social rights of women, including the right to free, compulsory education that notably influenced the incorporation of women in soil science. The 1917 revolution marked a turning point in the training of Russian women, as although they had been able to attend advanced courses in the schools of Agronomy and the Faculties of Natural Sciences before this time, they were not granted full access to university courses until after 1917.

Sycheva (2003) distinguished several stages in the process of the incorporation of women in soil science. The first generation is represented by women who were born before 1898 (total number = 11 researchers) and those born between 1898 and 1918 (total number = 75 researchers). The first women soil scientists were microbiologists, chemists and agronomists, and the results of their research studies were published in 1906–1907 by V.A. Bal´ts and V.A. Domracheva (1906–1907). The first female scientists known to be successful soil scientists were E.N. Ivanova, N.N. Sushkina and Z. Yu. Shokal´skaya. Most female soil researchers (born between 1898 and 1918) began their careers in the mid-1920s–1930s. They worked in research centres and universities created in the republic of the Sovietic Union in the study of the soils of these regions, also occupying positions of responsibility, acting as Laboratory and Department Heads and managing different scientific organizations/entities.

The second generation of female soil researchers (born between 1919 and 1938) began their careers in the mid-1940s–1960s (total number = 157 researchers). Many male scientists were killed in the Second World War, and in the postwar period, the proportion of female soil scientists who carried out educational and research tasks increased considerably as females occupied the vacant positions. In addition, large scale research programmes were undertaken, including the development of practices for the management and conservation of agricultural and forest soils with the ultimate goal of increasing soil productivity. At this time, the proportion of females in leadership roles reached the highest levels in the entire history of Russian soil science.

The third generation of female soil researchers (born between 1939 and 1958) began their careers in the mid-1960s–1980s (total number = 93 researchers). This period, during which Brézhnev´s government was in power, is associated with an economic recession that also had an enormous impact on the development of soil science. The research programme for the implementation of soil management practices aimed at increasing soil productivity continued, and women held leadership positions, although fewer than in the previous generation.

The fourth generation of female soil researchers (born between 1959 and 1978) began their careers in the mid-1980s (total number = 11). This period coincides with the economic crisis that caused a drastic reduction both in the number of soil scientists and in the government budget for research in soil science, especially fieldwork. Foundations such as the Russian Foundation for Basic Research were created to finance soil science investigation.

These female scientists contributed enormously to the advancement of soil science in Russia, given that, on the one hand, they developed new lines of research and, on the other hand, they continued the work of other lines developed by men and mainly involving fieldwork (i.e., genesis and soil formation, soil classification and soil mapping). These women scientists opened up new research lines related to the living fraction of the soil, i.e., study of the dynamics and composition of the soil organic matter (biochemistry and microbiology, micromorphology, processes) and also to the ecology and protection of soils (**Supplementary Table S1**). The study of processes related to the organic matter dynamics is complex and requires a great deal of meticulous work. It is precisely these lines of research developed by women and related to the concept of soil as a living system (soil quality and health, ecosystem services, microbial biodiversity, soil recovery) that have been longer to become accepted in Europe and in other countries worldwide. By contrast, the lines developed by men have undergone enormous development throughout the history of soil science.

Many of these outstanding women not only initiated new lines of research but also created schools of thought that have been fundamental to the economic development of Russia since they are related to the exploitation of virgin soils in different regions located in the countries that were incorporated the Soviet Union (**Supplementary Table S2**). These researchers later studied several aspects of the conservation and recovery of the productive capacity of soil after the implementation of various agricultural and forestry practices. They were supervisors of numerous doctoral theses by scientists from several countries (Russia and Soviet Union, Poland, Bulgaria, Romania, Yugoslavia, German Democratic Republic, China, Vietnam) who visited and worked in their laboratories. Likewise, the secretarial work and that of laboratory and field assistants and technicians was also largely carried out by women. Despite its great importance in the development of research, this work is generally not recognized by the scientific community. On the other hand, these scientists are women, wives and daughter, who must reconcile their work with the other family-related tasks, such as caring for children and the elderly.

The number of PhDs and the total number of papers published per author are considered indicators of the excellence of the researchers in a country: 132 of the 345 women soil scientists in Russia (132 PhDs and 60 postgraduate soil researchers) produced more than 50 publications. The scientific productivity is as follows: 300 publications, 6 authors; 200–299 publications, 31 authors; 100–199 publications, 76 authors and

50–99 publications 53 authors. Six outstanding women soil researchers published around 300–400 scientific papers (N.I. Bazilevich, L.M. Burlakova, A.A. Shtina, T.N. Kulakovskaya, G.Y. Merzlaya and V.V. Tserling). The most significant scientific papers were published in review journals; i.e., 148 women researchers published articles in the well-recognized internal Journal "Soil Science". Taking all of this into account, it is not surprising that many women took part in the leadership of the Russian and Soviet Society of Soil Science, such as members of the Central Council and science managers and therefore received numerous awards from both the government and various scientific institutions in recognition of their teaching, research and management work in the field of soil science (**Supplementary Tables S2, S3**).

The previously mentioned book (Shyeva, 2003) reports the first study that covers the contribution of Russian and the USSR women scientists to the development of soil science since the early 19th century, using a very reliable database. Soil scientists worldwide should have access to this valuable, detailed information on gender equity in soil science (names, fields and lines of research, scientific achievements, relevant publications and detailed biography of 345 women). We encourage Russian women scientists to translate this book into English and update it with the information about the new generations of female soil scientists.

Shyeva (2003) distinguished four generations of Russian and Soviet women soil scientists (one generation covers a period of about 20 years). As the book was published in 2003, there is now a fifth generation of women soil scientists (born between 1979 and 1998), who began their careers in the mid-2000s–2020s. In 2006, women constituted more than 60% of soil scientists (staff members of research and educational institutes); however, they did not influence the future of soil science in Russia due to the fact that their role in decision making was reduced to a minimum, especially in Moscow (Sycheva, 2006).

CURRENT CONTRIBUTION OF WOMEN FROM DIFFERENT COUNTRIES TO SOIL SCIENCE

The gender perspective is a key aspect that must be taken into account in numerous activities, such as resource distribution, legislation and policy development, as well as in encouraging dialogue and in the planning, implementation and monitoring of initiatives and proposals (UN, 2001). However, studies concerning gender equity in soil science are scarce and very recent. To date, we have found only one relevant international study (Dawson et al., 2021) and a few national studies, in the USA (Vaughan et al., 2019) and Indonesia (Fiantis et al., 2022; Hairiah et al., 2022). Overall, despite the greater number of women occupying postdoctoral and PhD positions in soil science in the last decade, the field remains dominated by men (in relation to senior, permanent positions, success rates in obtaining grants, keynote speakers at soil science conferences, editorial boards, invitations to referee scientific journals) (de Vries, 2017, 2020). In response to this problem, de Vries has established a network as a resource for use by event/conference organizers, journal publishers and sponsors to include women's participation in such activities (https://franciskadevries.wordpress.com/women-insoil-science/). We encourage women soil researchers in all countries to register in the "List of women in soil science" created by de Vries. Other studies include a brief biography of the women who are pioneers in soil science in Western countries (Helms, 1992; Levin,1998; Koziell 1999; McIntosh and Simmons, 2008; Cordero et al., 2021; Gerasimova, 2022; Reyes-Sanchez and Irazoque, 2022). Likewise, the mission of the organization Women in Agriculture Science is to increase the visibility of women´s roles in the agricultural sciences by sharing their life stories, successes and obstacles (https://www.womeninagscience.org/). It has been shown that reading biographies of scientists, especially about the struggles they have overcome, stimulates students learning and their interest in science (Hong and Lin-Siegler, 2012). Therefore, we call on teachers of soil science worldwide to use biographies of women soil researchers to inspire scientific vocations in girls and women.

The first paper on international gender equality in soil science was published recently (Dawson et al., 2021). This study used data on the memberships of 44 national soil science societies in 2020, the keynote speakers at three international conferences held in recent years (the International Union of Soil Science, IUSS, the World Congress of Soil Science, WCSS, the Soil Science Society of America, SSSA, and the European Geosciences Union Soil System Science Division, EGU-SSS) and the editorial board of nine Q1 soil science journals in 2020 (Applied Soil Ecology, Biology and Fertility of Soils, Catena, Geoderma, European Journal of Soil Science, SOIL, Soil Biology and Biochemistry and the Soil Science Society of American Journal). The study findings showed the following: 1) in most of the soil science societies, the proportion of men was much higher than that of women (68% versus 32%); 2) the average proportions of women speakers at WCSS and SSSA meetings were very low, 6% and 21%, respectively; and finally, 3) the proportion of women soil scientists holding positions on the editorial boards of the journals was 30%. The study also showed that the number of women who acted as keynote speakers have increased notably over time.

In the US, there has been great interest in the last 40 years in the status of soil science education. Several aspects related to undergraduate enrolment in universities and to guidelines for degree programmes that attract and recruit young male and female students to work as soil researchers have been addressed (Brevik, 2019). In addition, the status of girls and women in soil science in the US has been studied from the perspective of gender, and statistics concerning the level of participation, the obstacles and the challenges and opportunities that girls and women encounter throughout their scientific careers have been reported (Vaughan et al., 2019). These researchers observed that the enrolment of women in soil science has increased remarkably in the past 4 decades, with similar numbers and women and men undertaking advanced and master's studies. However, the proportion of women who have continued their studies and who have found positions as soil scientists is still much lower than that of men (with women representing 25% of the total). The study also revealed that women encounter more obstacles than men throughout their scientific careers. Thus, women soil scientists are under-represented in leadership positions and, despite the increasing involvement of women in soil science, their accomplishments are not well recognized. Available data on the representation in soil science of historically marginalized groups in the United States, including women, as well as the mechanisms involved in this process have recently been examined from historical and contemporary perspectives (Carter et al., 2021). These researchers also provide recommendations for implementing actions aimed at enhancing and emboldening diversity and inclusion in soil science. To broaden participation in soil science, the SSSA now provides several options for the (voluntary) recording of gender data on members: female, non-binary gender, male, and prefer not to answer. Thus, using this new database of SSSA membership (2019), which includes gender and ethnicity, these researchers have shown that women are generally represented in the same proportions as members from minority groups (21%).

The first study concerning the participation of women and men in soil science in Indonesia was also recently published (Fiantis et al., 2022). These researchers found that the number of students enrolled in soil science courses has increased notably in recent years, with the proportion of women reaching, on average, 56% (range 30%–70%). By contrast, a gender imbalance was observed among the course lecturers (average proportion of women lecturers, 30%). This observation was attributed to the fact that women must reconcile their careers with the tasks of caring for the family (children and the elderly). The data showed that women lecturers remain underrepresented, only 3% of soil science academics, while men accounted for 12%. Students considered that soil science would be better taught by male lecturers, but preferred female lectures as supervisors of final projects and master's or doctoral theses.

The greater participation of women in teaching and research in the discipline of soil science is reflected in the number of publications (Hairiah et al., 2022). Thus, proportions of male and female authors of scientific publications were similar (in 2019). However, the participation of women and men in the different tasks involved in the study of soil science (laboratory, greenhouse and fieldwork) is still not equitable, given that fieldwork is generally carried out by men, and greenhouse studies and, above all, laboratory studies (soil physical, chemical and biological analyses) are carried out by women.

The information presented here provides a brief analysis of the historical contribution of women to soil science from the perspective of two researchers who are specialists in respectively soil microbial ecology and philosophy. Therefore, the study has many limitations related to both the scarce knowledge about the history of soil science and soil science education of the authors and the scarce information available. The data presented, though incomplete, are meant to serve as a critical starting point to raise awareness among researchers about the urgent need to carry out gender equality studies in soil science worldwide, especially in Spain.

CONCLUSION

In summary, this study reinforces the idea that soil science is not neutral, that it is social and gendered and always will be. However, we must try to make it more inclusive. The data also reveal that although information on the role of women in soil science is limited, women are under-represented in all countries included in gender equality studies. Continued efforts must be made towards achieving gender equality in soil science. Equality between men and women is a very complex issue that depends on many factors (family, society, government, politics, geographical location, institutions and culture) that must be taken into account in any study of this type. Further research should be carried out worldwide, as the economic, political and cultural contexts determining the incorporation and changes in the contributions of women to soil science vary widely across countries. Therefore, recognition of and support for women soil researchers worldwide is needed to attain gender equality and improve education and research in soil science in order to better serve and protect soils and humanity.

AUTHOR CONTRIBUTIONS

MD-R: conceptualization, data analysis, and writing original draft. CC: conceptualization and writing original draft.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/sjss.2022.10658/full#supplementary-material

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Maria Glazovskaya—A Pioneer Soil Scientist and Geochemist Ahead of her Time (1912–2016)

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In the USSR and in Russia, women predominated among soil scientists despite the problems related to field research in tundra, taiga, mountains and other severe environments. One such woman was Maria Glazovskaya, who worked in highlands and semi-deserts studying little known soils, both recent and relict, primary pedogenesis, and geochemical features of hard rock weathering. Her scientific interests were diverse, and corresponded well with the social and scientific trends of the moment. She put forward new ideas and applied existing ones in several spheres of soil geography and landscape geochemistry. She proposed new approaches for compiling soil and landscape-geochemical maps, including using soil properties to predict the risks of soil pollution with heavy metals, and using landscape-geochemical methods to prospect for economic minerals. In the interdisciplinary conceptual sphere, Glazovskaya tried to bring together soil science and landscape geochemistry, and included these two subjects in the name of the department in Moscow University that she headed for more than 30 years. She was a scientist always looking for her own way in the interdisciplinary world of earth science.

Keywords: biography, centenary, soils, geochemistry of landscape, geography

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INTRODUCTION

Maria Alfredovna Glazovskaya (1912–2016)—a well-known Russian (Soviet) soil scientist, physical geographer and geochemist, Head of the Department of Soil Geography and Landscape Geochemistry in Moscow State University for more than 30 years, author of fundamental manuals on soil science and soil geography, small-scale soil maps; Honorary Professor, Vice-President and Honorary Member of the Dokuchaev Soil Science Society and the Russian Geographic Society. She prepared more than 20 PhD students and 10 Doctors of Sc. in Geography. Her last book–her memoirs–was written as she approached her 100th birthday.

Maria Alfredovna was a highly educated and charming person, extremely tolerant of other people's opinions and activities. If she disagreed with someone's judgment, she discussed it listening very attentively, asked questions, tried to understand the standpoints of her opponent, and finally said that, unfortunately, she could not support his or her argument. She herself had many ideas, and was happy if her students or colleagues assimilated them without accrediting her. In such cases she said: "OK, it is not important, but it proves that the idea was good". Although many of her ideas were implemented by students and colleagues in publications, she preferred not to join them and instead be the sole author of her books and articles. It may be that she did not wish to share responsibility for ideas that were not always in line with traditional concepts.

FIGURE 1 | Early research works in the 1950s.

FIGURE 2 | Head of the Department, early 1960s.

BIOGRAPHY AND SCIENTIFIC ACTIVITIES IN SOIL SCIENCE, LANDSCAPE GEOCHEMISTRY AND APPLICATIONS

A brief summary of the life and career of Maria Glazovskaya is presented here along with a few references to the situation at the time in the country and in science. Her last book of Glazovskaya (2012b) is entitled "My Life at the Background of Wars and Revolutions". Her contribution to Earth Science is discussed in sections with special emphasis on Soil Science.

Biography

Maria Glazovskaya was born on 26.01.1912 in Saint-Petersburg; she had a younger sister, Margarita, and their mother had an office for printing, editing, and translating books and documents. In 1919, during the Civil War, the family had to leave the city because the termination of orders meant the absence of work. They moved south in an overcrowded train, hoping to find somewhere a place with work and food.

Maria's mother was lucky to find work as teacher in a small village in Belarus, but soon she fell ill with typhoid, and Maria had to look after her mother and her younger sister during an extremely cold winter, without money and with only potatoes for food. In 1922, they returned to Saint-Petersburg (Leningrad), and after secondary school, Maria entered Leningrad University, the Geological-Soil-Geographical Faculty. As a student, she listened to the lectures of outstanding scientists–L. S. Berg, K. K. Markov, B. B. Polynov–and participated in expeditions to the Caspian Lowland. In 1934, Maria Glazovskaya became a post-graduate student of B. B. Polynov (future Academician), whom she regarded as her teacher all her life. Her first publication in 1936 concerned coastal salinity. In 1937, she successfully defended her PhD thesis "Soil Cover Micropatterns in the Caspian Lowland".

In 1936, Maria Glazovskaya married a geographer, Vitaliy Gordienko. He received a job in Alma-Ata (then the capital of Kazakhstan), and they moved there and lived happily, traveling in the mountains and studying landscapes and soils, until the beginning of the Second World War (**Figure 1**). Vitaliy was obliged to join the Red Army as an artillerist and was killed very soon after in Belarus.

Maria Glazovskaya stayed in Alma-Ata until 1952 and worked in the Soil Science Institute along with several other high-professional scientists who were driven to Kazakhstan by the war, and this period was creative for all of them as well as for local science. In 1952, she defended her Dr.Sc. thesis "Inner Tien Shan as a mountainous country of Central Asia" in Moscow, and was invited to the recently organized Department of Soil Geography in Moscow University, in the Faculty of Geography.

From then on, Maria Glazovskaya lived in Moscow and participated in numerous expeditions, which she arranged by

FIGURE 3 | Almost 100 years old.

locating interesting and diverse objects for study. Some were within the framework of Government programs. The first expedition was to the Southern Urals, targeted at developing geochemical methods to search for economically valuable minerals. Following this was extensive research on oil pollution in the Perm Pre-Urals area and effect of oil mining on soils. Then, there was a project in the Novgorod region within the "Man and Biosphere" International project in the 1970–1980s. As the Head of the Department of Soil Geography in 1959–1987, she initiated these and other projects involving many specialists and students (**Figure 2**).

As a Professor, she lectured on basic courses ("Fundamentals of Soil Science", "Geochemistry of Landscapes of the USSR", "Technogenic Landscapes") and more specialized courses ("Geochemical Functions of Microorganisms", "Geochemical Methods for Ore Minerals Prospecting"). An obvious emphasis on geochemistry was the reason the name of the department was changed to "Landscape Geochemistry". However, Soil Science always remained an important sphere of Glazovskaya's interest and activities, both in research and teaching, as well as a basis for new trends in the geochemistry of landscapes. Following her retirement, Maria Glazovskaya continued her intensive work as a Consulting Professor. At the age of 96 she prepared a monograph entitled "Pedolithogenesis and Continental Cycles of Carbon" (Glazovskaya, 2009), that summed up the results of her own studies and those in publications (**Figure 3**).

Contribution to Soil Science

Chronologically, the first study objects of Maria Glazovskaya were arid lands. After the Caspian Lowland with salinity issues, she worked in Kazakhstan, where she performed the routine work of a soil scientist: describing soils in the northern semi-desert which were not well-known then, including various Chestnut and Brown Soils (Calcisols in WRB), and compiling maps. Her work in the highlands was quite different: creative and exotic, although not easy. Her research topics included the weathering of hard rock as affected by microorganisms and the contribution of aeolian phenomena to pedogenesis. The initial signs of pedogenesis on glaciers were investigated in high mountains around the Lake of Issyk-Kul'. Her biogeochemical approach was manifested later as well, it concerned the ash composition of plants as a "trigger" for the solonetzic process on the plains in the areas of Chestnut and Brown aridic soils (Kastanozems and Calcisols). Maria Glazovskaya performed one more "exquisite" case study in the northern countries: in Scotland and Estonia, she gave comprehensive characteristics to soils with spodic elements–soddy subarctic soils and podzols in catenas.

Maria Glazovskaya is known to Russian soil scientists as the co-author (with Innokentiy Gerasimov) of a famous textbook "Fundamentals of Soil Science and Soil Geography", (Gerasimov and Glazovskaya, 1960). It was very popular in the USSR/Russia, and was translated into English and included in the 200 best publications in soil science in the world; its conceptual background remained almost unchanged until recently. "Soils of the World" is another well-known textbook in two volumes (Glazovskaya, 1972-1973; English versions published in 1983 and 1984 Glazovskaya, 1983). She had very few chances to visit foreign countries; however, a great volume of information on landscapes and soils was collected by Glazovskaya in the literature sources available in the Soviet Union. Soils of all continents (except for Antarctic) were described in detail in these books, and of special interest was Australia: in 1952 Glazovskaya published a small book on the soil geography of Australia based on her great experience in aridic soils and on the data of Australian soil scientists who were followers of Dokuchaev's paradigm, and of their scientific leader, Prof. J. Prescott, in particular (Glazovskaya, 1952). During the ISSS World Congress–1968 in Australia, in which Soviet soil scientists were permitted by State authorities to participate, Maria Glazovskaya had a wonderful chance to visit J. Prescott and to cross the continent (Adelaide-Darwin) as a participant of the scientific excursion. J. Prescott knew her book, they discussed Australian soils, and he was amazed at her deep perception of soils as related to regional environments.

In her textbooks on world soils, Maria Glazovskaya implemented some elements of her ideas on soil classification and the most general, or global, regularities of soil geography. Her system of world soils is frequently regarded as soil classification, but that is not completely correct since it concerned only the higher taxonomic levels. In the system advanced by Glazovskaya, priority was given to physicochemical soil properties: pH + redox potential at the highest level, main soil-forming processes at the next level, type and composition of pedogenesis products formed the third level comprising groups of soil types.

In accordance with her grouping of soils, Maria Glazovskaya proposed an innovative perception of soil geography. The traditional zonal approach was not the main criterion for specifying spatial units; she paid more attention to soil properties, relief, parent material and types of soil-geochemical catenas. This was a hierarchical system of soil-geographical zonation.

Conceptually close to this system was the World Soil Map compiled together with V.M. Fridland and published in Glazovskaya and Fridland (1982), scale 1:15 million. This map was part of a special series of maps "For Higher School"; therefore, its legend was organized in a simple, but rather unusual, way: it was a matrix with two entries - Hydrological regime of soils and Heat reserves. Cells of this matrix contained several soils with similar physicochemical properties. The map's legend comprised 96 soils, and the spatial information on their occurrence was taken from Russian small- and medium-scale maps, and from some sheets of the FAO/UNESCO World Soil Map that were published and available. The map has been actively used until now in lecture courses on soil geography and soils in many universities and institutes in Russia.

Contribution to Landscape Geochemistry

While the scientific contribution of Maria Glazovskaya to Soil Science was conceptual and concerned broad spheres of pedology, her activities in geochemistry were more methodological and oriented on applications. It started in the expeditions she initiated to the Southern and Central Urals in the 1960s as a reaction to the "explosion" of geological investigations in the country and in the search for more indirect and less labor-intensive methods than those that existed in geology. The Ural Mountains with their enormous mineralogical richness were an ideal place for such research. Many young specialists were involved, and they were enthusiastic to explore new regions with new geochemical methods; chemical analyses were made of heaps of soil, plants, and rock samples to reveal geochemical anomalies indicative of precious economic minerals. In this period, a new scientific school of landscape geochemists was formed, and they considered Maria Glazovskaya among their leaders. They had their "textbook" – a book by Maria Glazovskaya entitled "Geochemical Fundamentals of Typology and Methods for Studying Natural Landscapes" (Glazovskaya, 1964); soon, it became a rarity and was re-published in 2012.

After the "golden age" of landscape geochemistry (1960–1970s) came the period of accumulating facts and looking for regional and local patterns. This work was performed by post-graduates from Moscow and other regions under the supervision of Maria Glazovskaya, Alexandr Perelman and Nikolay Kasimov. Among the study objects were geochemical catenas and barriers in various regions. The theory of geochemical barriers forwarded by A. Perelman, was further advanced and extended by Glazovskaya (2012a), and it became helpful in tackling technogenic landscapes, their sequences, and their soils.

Contribution to Technopedogenesis and Ecological Risks

Maria Glazovskaya introduced in 1986 the notion of "technopedogenesis" - a soil-forming process affected by diverse human interventions. Three examples were discussed in her first publication on the subject: paleosols of burial mounds, intensively irrigated Chestnut soils, and assemblages of soils modified by oil spills (Glazovskaya et al., 1986). The latter theme became one of the main research areas in the department, and it was guided by Nina Solntseva - a faithful pupil and follower of Glazovskaya (Solntseva, 2009). The research is interesting in terms of soil genesis in situations when human impact is incompatible with the natural pedogenesis: soddy-podzolic soils (Albic Retisols) of taiga accumulate soluble salts from raw oil, so solonchak and solonetz properties appear in these acid soils.

Soil properties as key objects for understanding the natural environment always attracted the attention of Maria Glazovskaya. We have already mentioned her addressing soil properties as classification criteria, as the results and manifestations of pedogenesis, and interpretation of soil horizons as radial geochemical barriers. In the 1980–1990s, many scientists were preoccupied by the problems of soil vulnerability to technogenic pollution, a specific term was even proposed, "Chemical Time Bomb." This presumed that if the accumulation of toxic substances in soils reached a certain level, it could become dangerous. Revealing such time bombs was a challenge for soil scientists, since most pollutants were heavy metals. Soil resilience was evaluated by diverse methods, quantified, prognostic maps were compiled, and several international conferences were arranged on soil pollution, vulnerability/resilience and assessment of risks (Glazovskaja et al., 1991). Maria Glazovskaya and her team already had experience in compiling small-scale soil-geochemical prognostic maps. Risks of pollution (from weak to strong and even critical) were shown on such maps for individual pollutants like zinc, lead, arsenic, etc., and their associations. Risks were assessed by interpreting properties of various soils responsible for soil capacity to accumulate or modify pollutants in each soil, hence, soil units of a soil map were transferred into mapping units on a prognostic map. Information on pollution sources, such as waste emitted that contained certain elements, or urban or mining dust was added. Another ingredient of a prognostic map was the permissible concentration of an element, information which could be used to evaluate risk in a user-friendly format. These methodological issues were thoroughly analyzed by Glazovskaya and, along with her own experience, served as a basis for the guidelines "Methodological Base for Assessing the Ecologic-Geochemical Resilience of Soils", 1997.

The last scientific publication by Maria Glazovskaya was the monograph "Pedolithogenesis and Continental Cycles of Carbon," where extensive information was collected and analyzed to evaluate the contribution of soils to global carbon pools. The calculation of the carbon dioxide budget in the "atmosphere–pedosphere" system for the period 1985–2008 for Eurasia revealed a certain imbalance, hence, a possible sink of carbon somewhere in the pedosphere. It was shown that this sink may be due to the fossilization of pedogenic carbon, including that of carbonates in deep layers of the pedosphere, which is regarded as an ingredient of the pedolithosphere. It was suggested that data on pedogenic carbon needed to be considered in developing prognostic models of the carbon budget and climate warming.

CONCLUSION

Even in this short overview, the great diversity of scientific areas in which Maria Glazovskaya found her research objects is obvious. Her first steps in science were dual: the aridic soils of the Caspian Lowland and Turgay Plateau (Northern Kazakhstan) and the Alpine landscapes of the Central Asian mountains. Two trends were always obvious in her activities, and they are reflected in the name of "her" Department–Soil Geography and Landscape Geochemistry.

At the same time, Maria Glazovskaya tried to unite these two trends, understanding well that they are mutually enriching. In her early research, knowledge of soils and their occurrence was helpful in the search of geochemical anomalies, and the anomalies explained some peculiar soil features; radial geochemical barriers would be impossible to find without interpreting soil horizons in the profile. The technopedogenesis concept she introduced might be regarded as a quick-acting or current model of pedogenesis.

In those times when she worked and had many ideas, few contacts with the western world of science were possible. Now, realizing the scale of her achievements, we can only regret that her scientific accomplishments were so little known beyond the USSR/Russia. In Russia, geographers and soil scientists remember her with immense respect, love, and gratitude; and they frequently return to her ideas.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

CONFLICT OF INTEREST

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Reevaluating Diversity and the History of Women in Soil Science: A Necessary Step for a Real Change

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Over the last decades, diversity in science has focused on the inclusion of individuals from formerly under-represented backgrounds. While this is important, it can result in reducing the topic to a game of numbers and quotas, but individuals are not numbers. Science today must include all that a human can be, and this means both to include the under-represented and the represented. As a group endeavor, science can only be as good and innovative as the sum of its individuals' brilliance, because of this, science needs to ensure it has the largest pool of individuals to choose from. In the same sense, now more than ever, soil science faces problems that come from complex causes and require interdisciplinary equally complex solutions, meaning that it requires minds with different perspectives, different skills, and different life histories. Minds that contribute diverse knowledge and visions to the soil's preservation so that it maintains its properties and ecosystem benefits over time: minds capable of making soil's sustainable use. While only two aspects of diversity (the recognition of Women and Traditional Knowledge in soil science) were analyzed in this document, is an attempt of broadening the understand of diversity and their fundamental importance to achieve soil sustainability and contribute to reach the UN sustainable development goals (SDGs) as has been widely documented in FAO (2010), mentioned in Reyes-Sánchez (2018) and discussed in Dawson et al. (Eur J Soil Sci, 2021, 72, 1929–1939).

Keywords: gender, equity, soil science, women in science, diversity and inclusion

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INTRODUCTION

Over the last century and a half, the western world has tied the word diversity to three iconic movements that helped recognize women's rights, civil rights, and LGBTQ + rights (Library of Congress, 2022a; Library of Congress, 2022b). These fights are so inspiring and important for each generation, that it is only normal that our attention made intense focus on each of these specific areas of diversity. Nevertheless, in doing such an intense focus, we might have excluded from our perspective the main and broad meaning that the word diversity has.

Narrowing the meaning of diversity and inclusion has brought intense polarization around this topic. In some instances, it could seem that talking about diversity means removing quality as the main criterion for moving upwards in any discipline, or that we are suddenly trying to exclude certain population groups as punishment for the past. However, no scientific discipline has ever benefitted from narrow views, and soil science is not the exception.

Diversity, Going Back to the Basis

The first references in the English language for the word "diverse" come from the 14th century as a loan from Latin meaning "turned in different directions, situated apart, differing" (Merriam-Webster, 2021). If we start anew from this point, diverse and diversity seem a lot less radical and polarizing because they simply mean different and variety.

It is not possible to have variety when one has a single object or subject, this helps us understand that plurality is the basis for diversity, an individual cannot be diverse, but groups of individuals can possess diversity (Gibbs, 2014). For purpose of this article, our group could be the international community of Soil Scientists.

Over the last decades, diversity in science has focused on the inclusion of individuals from formerly under-represented backgrounds. While that is not unimportant, bringing diversity to Soil Science means including individuals with different skills, different political views, coming from different backgrounds, from all genders, or that identify with different sexualities and might be gender non-conforming, that belong to different races, and that have disabilities, among other identifying features and factors. When we read this list, it is easy to feel overwhelmed at the size of the task; however, this feeling can dissipate if we go back to the basics once again. We are simply asking to allow inclusion of all scientists based on their professional qualifications, and to not make any exclusions based on the above-mentioned or similar identifying features and factors.

Making science is the process of understanding and solving complex problems. In soil science, problems such as salinization, degradation, acidification, and nutrient imbalance, are all complex problems and in need of interdisciplinary and urgent solutions that likely cannot be found by an isolated single individual in a single moment in time. Instead, the process of solving complex problems requires the effort of a group of individuals, or multiple groups of individuals, over time. This is where diversity becomes essential because the ability to see complex problems from different perspectives cannot be achieved if all the individuals in a group share the same perspective.

Quality in science is closely linked to the quality and brilliance of the scientists as individuals; including all that a human can be, means that our pool to search for brilliance grows, that the quality of the training that our soil scientists get will increase, and that soil science will increase the impact it has to apply necessary changes in the real world out of the laboratory and classroom.

SCIENCE AND SCIENTISTS: A REVIEW OF TIME AND GENDER

It is hard to understand why diversity and inclusion are necessary for science if we continue to believe that science started only a couple of centuries ago from a male-centered scientific community. Hence, we propose a quick exercise in reviewing science from its inception and scientists from its most basic gender composition.

Science and Soil Science as Human Endeavors

When we talk about Science, the common image of a person in a laboratory wearing laboratory coat and laboratory goggles may come to mind; after all most of us grew during the last decades of the 20th century and have indeed developed scientific careers inside a laboratory. However, a quick review of literature on the History of Science can easily show that scientific practice can be formally traced back at least to Ancient Egypt and Mesopotamia starting from the fifth century B.C. (Lindberg, 2007).

In the same sense, if we think of the origin of soil science, the name Vasily Vasilyevich Dokuchaev likely comes to mind. However, if once again, we think about the history of science, we can understand that it is impossible to pinpoint the start of our discipline a mere century and a half ago.

As soil scientists, we recognize that soil is a vital resource for life on Earth and as such, it is only natural that its study has been common to all human societies for thousands of years, even before the advent of writing systems. What this means, is not that we should reduce the merits of great soil scientists such as Dokuchaev, on the contrary, it means that we should also recognize the merits of great human thinkers that paved the way for our discipline.

Today we know that approximately 9,000 years ago our ancestors in Mexico domesticated maize from a plant named *teocintle* (Beadle, 1980; Matsuoka et al., 2002), which could only have been achieved through observation and experimentation, two main pillars of the scientific method involving substantial knowledge and technique not only about the domestication of plants but also about soil and water management for the development of agriculture.

This is a clear example of how, as with any other area of science, the real point to start tracing history is with indigenous people. Indigenous people have traditionally occupied territories in all regions of the world, except for Antarctica; today they compose 5% of the world population accounting for approximately 400–500 million people (UNESCO, 2022a). Indigenous people are responsible for the conservation of 21% of the world's soil resources (ICCA Consortium, 2021), which are key to soil science and many other areas of science; in contrast, even in advanced countries, indigenous people barely represent 2% of the composition of studies in STEM. Another important aspect that we need to recognize is the role of indigenous knowledge and indigenous decision-making systems as an important national resource that has been ignored, neglected, and sometimes maligned (Warren, 1989). In this sense it is key that the soil science community make clear efforts to include indigenous communities in its ranks, and to recognize the role of indigenous traditional knowledge in their research and conservation practices.

Half of the World, Half of Soil Science

In the same way that during centuries formal science did not provide proper credit to traditional knowledge and indigenous communities, during many centuries formal scientific institutions precluded women from entering their ranks. The 2019 Revision of World Population Prospects report (United Nations, 2019) shows that 50.4% of the human population is male, while 49.6% is female. Data of this type naturally does not reflect variation per country or life expectancy but does show a very evident truth. Women and men are each, on average, half of the human population. Today, women constitute half of the agricultural workforce around the world (World Bank, 2017), and any efforts to overcome the complex problems that endanger the soil resource need to include women in its study, solution design, and application. However, when we closely observe the international community of Soil Scientists as our closely selected group of study, we can immediately notice that it does not reflect the above-mentioned balances on gender. In reviewing the participation of soil science societies around the world, one can find that women constitute only 32% of their members (Dawson et al., 2021). Taking the United States as a sample, women constitute 50.52% of the country, they hold half of the degrees in soil science, yet they only hold 24% of the academic faculties' positions in that same area (Vindušková et al., 2021). When go through a similar exercise in reviewing inclusion statistics for to race and origin we can find that in the United States 88% of doctoral degrees in Soil Science correspond to people of white race, 9% to Hispanics, 3% to black people, and an appalling 0.1% for native Americans (Carter et al., 2020) and (National Science Foundation and National Center for Science and Engineering Statistics, 2019). If we review the percentages that each of these populations actually represent in the US, we will find that white population is 61%, Hispanic is 18%, and black population is more than 12% (United States Census Bureau, 2021). It is evident that soil science's rates of diversity and inclusion are far from being a fair reflection of society. In the US, Soil Science doctoral degrees show less variety of different races than Agronomy, Geology, and Ecology, and all these areas show much less diversity than STEM in general (Carter et al., 2020).

WOMEN IN SOIL SCIENCE: THE PIONEERS IN THE XIX CENTURY

If we acknowledge that, despite political views and temporary trends, science is above all a human endeavor, we must then also acknowledge that no science can exclude any half of the population from its history. While very little can be found in the history of Soil Science to recognize the lives and labor of women that have contributed to this science the authors of this article want to identify the modern pioneers.

Mary Emilie Holmes

She earned a Master of Arts degree in 1882 and was the first woman to earn a doctorate in Earth Science from the University of Michigan, and in a US University in 1888. She became the first woman fellow elected to the Geological Society of America in 1889. She was an advocate for the importance of teaching geology early in children's education. University of Michigan website (2015), Schwarzer and Crawford (1977).

Florence Bascom

Florence Bascom was born in 1862 in Massachusetts, US. She earned two bachelor's degrees: a Bachelor of Arts in 1882, a Bachelor's in science in 1884, and by 1887 she earned her Master's degree in Geology, all at the University of Wisconsin. She became the second woman to earn a PhD. in Geology in the US and the first woman to earn a doctorate in the Johns Hopkins University. She also was the first woman to teach at Bryn Mawr College in 1895. University of Wisconsin-Madison website (2012), Schneiderman (1997).

During her studies at Johns Hopkins University, she was forced to take classes behind a screen so she would not distract her male classmates (Ignostofsky, 2016). As a teacher and researcher at Bryn Mawr College, she founded the geology program training many other female geologists and working intensely in geomorphology. Florence Bascom became an expert in crystallography, mineralogy, and petrography, and her studies and results in these fields of knowledge were essential to understanding the evolutionary mineralogical composition of rocks, which is fundamental for the study of soils. She was editor of the American Geologist, a member of the National Academy of Sciences, the National Research Council, and the Geophysical Union. In 1937, 8 out of 11 of the women who were part of the Geological Society of the United States were graduates of the Geology course that Florence Bascom taught.

A Woman in the Founding of the International Society of Soil Science

According to Van Baren et al., in 1924 "the Fourth International Conference on Pedology lasted from 12 to 19 May 1924 (**Table 1**) and was held under the patronage of the King of Italy and the auspices of the International Institute of Agriculture. The number of adherents to the conference was 463, representing 39 countries." As expected, and can be seen in **Figure 1**, at that time there were very few women who participated in scientific meetings.

During this Fourth International Conference on Pedology, six commissions were established: I. Soil physics; II. Soil chemistry; III. Soil biology; IV. Nomenclature and classification of soils; V. Soil cartography; and VI. Plant physiology in relation to pedology. These commissions formed the structure of the International Society of Soil Science (ISSS), which was founded during the morning session on the last day of the Fourth International Conference on Pedology, 19 May 1924 (**Table 1**).

Dr. Hermann Stremme and his wife Emma Marie Antoine Täuber, who was the first woman to graduate as Ph.D. in the subject of geology in Germany, were some of the attendees to the Fourth International Conference on Pedology in May 1924; this makes Emma Marie Antoine Täuber one of the few women who probably were present at the formation of the International Society of Soil Science (ISSS).

Emma Marie Antoine Täuber (Antonie Stremme-Täuber)

Emma Marie Antoine Täuber is the only woman whose presence and identity in the foundation of the International Society for Soil

TABLE 1 | Meetings preceding the formation of the International Society of Soil Science (ISSS) in 1924. Data was obtained from Van Baren et al. (2000).

Year	Meeting	Location	Number of participants	Important outcome
1909	First International Conference of Agrogeology	Budapest	86	Regularly organize agrogeological conferences
1910	Second International Conference of Agrogeology	Stockholm	170	Formation of three Commissions
1922	Third International Conference of Pedology	Prague	50	Formation of five Commissions
1924	Fourth International Conference of Pedology	Rome	463	Formation of the ISSS

Sciences we can assume given her usual presence at the Conferences of Pedology in Europe (Stremme-Täuber, 1957).

Emma Marie Antonie Täuber was born in Berlin on 31 January 1882, and died 4 August 1961. She studied Geosciences at the Berlin University from 1909 to 1912 and finished her studies in 1913 with a Ph.D. as the first woman in geology.

Her teachers were the geologist Wilhelm Branca (1844–1928) with Hermann Stremme (1879–1962) as private lecturer, the geographer Albrecht Penck (1858–1945), the mineralogist Theodor Liebisch (1852–1922), the petrograph Otto Erdmanns-Dörffer (1876–1955) the philosopher Benno Erdmann (1851–1921) and the theologian Georg Lasson (1962–1932) together with their assistants: She graduated as Dr. phil. at the end of 1912 as the first woman in the subject geology with the dissertation: Location and relations of some Tertiary volcanic areas of Central Europe to contemporaneous seas or large lakes. The subject of the thesis was based on the observation of others that during eruptions of some active volcanoes the release of water vapor had been observed and therefore an influence of sea or lake water was assumed (Täuber, 1913). Their studies could not confirm this. The work was recognized by the Faculty of Philosophy as the best dissertation of its year.

1912 followed the marriage with her teacher Hermann Stremme and worked in the following years as a scientific assistant in the institute of mineralogy, and geology of the Technical University of Gdansk. She also taught lectures of her husband while he worked as a military geologist in Romania and the Vosges. After the war, she worked cartographically for the Geographic Institute of the University of Berlin at the Institute for Soil Mapping of the German Administration for Agriculture and Forestry.

WOMEN IN SOIL SCIENCE IN THE US

According to Levin (2005), the women's work from 1895 to 1965 was limited to the administrative work of cartographic editing and drafting. In his work Levin (2005) refers that Janette Steuart was the first woman hired in 1895 to work for the Soils Division which was part of the Weather Bureau within the USDA; along with Sorena Haygood, Janette maintained laboratory and field records until her retirement in 1920. He also points out that in 1901, Julia R. Pearce became the first woman to graduate with a degree in agriculture from the University of California at Berkeley (UCB) and the first woman hired to work in soil survey; but unfortunately, she never had the opportunity to join in field trips, due to which she only did cabinetwork. Levin also indicates in his work that until 1950, women were not authorized to join in field trip studies of soils because that activity was reserved for men; hence women were only allowed to work in soil science editing, writing erosion history, and doing laboratory work Ibid.

Through his work, Levin (2005) documents that Ester Perry was the first woman to earn a Ph.D. in Soil Science from Berkeley in 1946 and became the first doctorate in soil science in the United States. She directed the USDA Soil Laboratory at UC-Berkeley until 1965. However, she never was acknowledged in the USDA records as an official soil survey collaborator. In 1951 Mary C. Baltz from Cornell University was the first woman hired to work in the field for the Soil Conservation Service (SCS).

GENDER EQUITY IN SOIL SCIENCE TODAY: AN INTERNATIONAL LOOK FROM THE IUSS SOCIETIES AND FAO

The UNESCO worldwide report in 2021 (UNESCO, 2021b) indicates that while a growing number of women are enrolling in university, only 30% of the world's researchers are women because many of them opt out not participate a research career due to the obstacles that women face in scientific fields. In the same vein, while women earn almost half of advanced soil science degrees awarded in the US, they only make up about a quarter of its soil science workforce (Vaughan et al., 2019). All the recent studies indicate that even though more women earn their doctorate in soil science, the number of women scientists in academic and research institutions, and actively participating in scientific Soil Science Societies, has strongly decreased, widening the gender gap in this area of science (Dawson, et al., 2021; Maas et al., 2021; Velander et al., 2021).

The bibliometric study of 5,483,841 research papers and review articles with 27,329,915 authorships carried out by Lavivière et al. (2013), indicates that even when the gap is different for different fields of knowledge, on average, men publish more articles than women. This trend increased during the COVID-19 pandemic because while the number of scientific publications increased during this period, the number of women publishing decreased because the lockdown increased the work of women at home, limiting their professional and scientific work by limiting the time they could dedicate to it (UNESCO, 2020a; Viglione, 2020; UNESCO, 2021c; Velander, et al., 2021).

According to de Vries (2020) and Vaughan et al. (2019), the fewer opportunities to be invited as main speakers, to be part of Committees, the difficulties they face in receiving funding for their research, the differences in salary and professional advancement opportunities they face concerning those of their male colleagues, and the difficulty in managing professional life in a balanced way concerning personal life, are only some of the most important reasons for the gender inequity that prevails in soil science, and also for the low percentages of women who work as soil scientists. To this we must add the obstacles that women in the scientific fields face because men in the scientific fields do commonly not establish respectful and egalitarian work relationships with them partly due to "unconscious bias." However, while "unconscious bias" is indeed important, it should never be used to avoid accountability for discriminatory behavior from individual scientists, nor to exempt the scientific community and the scientific institutions from their responsibility to address it through initiatives such as providing mandatory training about it, establishing firm guidelines to avoid it, and providing easy and non-retaliatory pathways to report cases of discriminatory behavior.

Indeed, there is no doubt that Soil science is a male-dominated field in most countries worldwide. In a recent study, Dawson et al. (2021) reported that from the data obtained from 44 national societies belonging to the IUSS in 2020: 37 out of the 44 societies had more male members than females, only 32% of the soil science society members were women, only one society had 69% female membership, and only 20% of the national soil science societies belonging to the International Union of Soil Sciences had a female president. Vaughan et al. (2019) report little progress in the US.

In 2012, within the Food and Agriculture Organization of the United Nations (FAO), a new context was set to address the "urgent need to raise awareness of the importance of soils and specially to protect and use them in a sustainable manner" (FAO, 2012), and the Global Soil Partnership was launched in Rome where soil scientists from around the world were invited to form the Intergovernmental Technical Panel on Soils (ITPS). The Global Soil Partnership (GSP) is coordinated by a General Secretariat working in collaboration with an Intergovernmental Technical Panel on Soils (ITPS). The ITPS is a working group composed of 27 top soil experts representing all the regions of the world (https://www.fao.org/global-soil-partnership/intergovernmental-technical-panel-soils/es/); 18 of their current members are men and 9 are women, then, although the ITPS is currently chaired by a woman, only 33% of the ITPS are women in 2021.

In 2019, the International Union of Soil Sciences, 96 years after its foundation, elected and for the first time has a woman as its president for the period 2019–2024 IUSS Alert (2018). The Latin-American Soil Science Society (SLCS), and the East and Southeast Asia Federation of Soil Science Societies (ESAFS) are two of the largest Regional Organizations of Soil Sciences Societies belonging to the IUSS and both have currently a woman as president. 30% of the Soil Science Societies that make up the SLCS have a woman as president (https://www.slcs.org.mx/index.php/miembros), and 22.8% of the Soil Science Societies belonging to the IUSS have currently a woman as president Dawson et al. (2021) and SLCS website.[1] Although these data represent a small advance on women's recognition as soil scientists and their capacity to perform successfully in the highest leadership positions in our professional societies and world organizations, they also show that gender equality in soil science is far from being achieved.

While in 2020 the ASA, CSSA, and SSSA Women in science Committee organized a workshop to help women in soil sciences develop skills to effectively deal with conflict, using emotional intelligence on important workplace issues, such as harassment, micro/macro aggressions, and bullying SSSA (2020). However, although this could surely help women face gender problems, this is not the solution because as long as men are not educated in a culture of equality, expressions of harassment, micro/macro aggression, and bullying will not disappear. The real change we need and must seek is not women resist or confront the gender gaps but that gender issues do not exist. Achieving this implies understanding that inclusion begins early when ideas are structured, and the identities of men and women are defined through an education that encourages and socially practices diversity, equity and equality. An education based on the full understanding that "equality does not mean that women and men will become the same but that women's and men's rights, responsibilities and opportunities will not depend on whether they are born male or female." UN Women (2021).

That is why today, worldwide, both organizations such as the UN and UNESCO as well as the NGOs and networks of women scientists warn about existing inequalities and the damage that these inequities mean for everyone in economic, scientific, social, and human terms. Organizations such as Earth Science Women's Network,[2] Frantecologist,[3] 500 womenscientists,[4] and UNESCO not only seek to recover the historical memory of the contributions made by women throughout the history of humanity but build future history from the registration and dissemination of scientific activities and achievements of women as means of struggle and empowerment.

As part of its efforts to collaborate with sister organizations in closing the gender gap and fighting for inclusion, in 2021, the IUSS signed a Memorandum of Understanding (MOU) with the Standing Committee for Gender Equality in Science of the International Scientific Council (ISC) International Union of Soil Sciences. Although this is not a simple task, the IUSS, needs to continue working hard to advance on this issue, and to demonstrate its commitment to promote, encourage and strengthen daily behaviors towards the construction of a culture of conscious recognition of our human equality. We need to do it because history shows us that seeking confrontation or social punishment to advance, is not the path, and on the contrary, for humanity, the pathway is the construction of a culture of equity, inclusion, diversity, and equality, so working on to achieve it is essential to close all the gaps.

[1]https://www.slcs.org.mx/index.php/miembros.

[2]Earth Science Women's Network https://eswnonline.org/resource/newsletter-ofthe-association-of-women-soil-scientists/.

[3]Frantecologist https://franciskadevries.wordpress.com/women-in-soil-science/.

[4]500 womenscientists https://500womenscientists.org/.

FIGURE 1 | Group photo from people attending the Fourth International Conference of Pedology, during the Formation of the ISSS in Rome, May 1924. © IUSS Historical Gallery: https://www.iuss.org/about-the-iuss/iuss-history/.

OUR TURN FOR DIVERSITY AND INCLUSION

Despite the undeniable progress made over time, gender inequalities are still present in the world in general and in scientific life in particular. According to UNESCO data (2020b), less than 30% of the world's researchers in the areas of engineering and mathematics are women, but they also receive lower salaries for their research.

For UNESCO (2021a), "women and men must enjoy equal opportunities, choices, capabilities, power and knowledge as equal citizens," however, the differences of gender, race, ethnic group, religion, political inclination, skin color, etc., are at the center of all non-inclusion within academia and science.

The current practices of non-inclusion are an inherent factor in gender inequality. Oral, written, and body language determine the social attitudes and behaviors that make up a culture, which can be inclusive or exclusive of gender, and which can explicitly or tacitly conform to gender prejudices and stereotypes thus limiting a sector of society from certain areas. From this derives the importance of promoting language that is non-discriminatory of gender, race, ethnic group, religion, political inclination, or skin color. That is why, all kinds of discriminatory languages between scientists and members of our scientific societies are not admissible in any case, and the reason because these practices must be rejected by all since no divisive practices are admissible, well they are the pathways that encourage the use and reinforcement all kind of discriminatory behaviors.

Soil science communities need to fight for changing the present situation because ensuring an inclusive and equitable quality education promoting lifelong learning opportunities for all is the point of link and interrelation between all the SDGs to achieve soil sustainability (Reyes-Sánchez, 2018). For that reason, within the scientific societies of soil science, we need to promote an education paradigm that recognizes the soil is not only a natural resource but also a social, economic, cultural, political, and patrimonial good *Ibid.*

The soil as a resource allows humans to live on it, and through our work it enables us to obtain food, water, and legitimate sustenance, which is essential to overcome poverty, to construct an identity and a culture, and to achieve economic independence. Gender-based discrimination in land ownership has historically been a crucial factor in determining the distribution of power and resources between men and women, and is a key obstacle to equity and equality; it is not possible to achieve equal economic independence without equal access to land ownership and land care (Reyes-Sánchez, 2018). Fighting for legitimate land ownership for all genders is a key element in achieving equality, in the construction of a just society, and in ending all forms of gender-based discrimination.

As mentioned before, UN (2020) data indicates that women and girls constitute half of the world's population and consequently half of all human capacities, which means that the participation of that half of humanity is essential for the enrichment of scientific, economic, and social activity for the achievement of the SDGs. It also means that failing to include half of the human population puts the sustainability of the soil and its biodiversity at risk, affecting food security, agricultural production as a fundamental economic engine, and the real possibility of mitigating climate change.

Similarly, UNESCO (2022b) celebrating the International Day of Women in Multilateralism on 25 January 2022, stated that "all forms of discrimination based on gender are violations of human rights, as well as a significant barrier to the achievement of the 2030 Agenda for Sustainable Development, and its 17 Sustainable Development Goals." That is why it is of the utmost importance to work in the continuous and conscious effort to include women and girls in all areas of human life.

Now is the time to act as scientists to review the current patterns of diversity and inclusion of our scientific community to apply the scientific method to the analysis of our behaviors. It is time to act and apply the scientific method, not only to observe, record, and analyze both the historical events and movements and the proposed hypotheses as possible solutions to the continuous and unjust absence of inclusion. We need to challenge those hypotheses to make it go through the falsifiability principle (Popper, 1959), like an indispensable step to advance toward building new progression hypotheses that allow us to move towards diversity and inclusion as the basis of equity.

We should now be at the point in time in which we should test the results of our actions. Soil Science should be able to pass the test to show what was learned and what actions were taken based on that diversity and inclusion are valued by its scientific community because it is only logical to infer that being composed of scientists, the community acts and decides based on knowledge and analysis.

However, from the statistics shown in this article, it is evident that the soil science community has not made enough efforts towards diversity; for gender, race, and origin, soil science has lower percentages of diversity than those of STEM in general, and much lower percentages of diversity than what the real population composition is in any country.

The important part about having clarity is to understand the message that our scientific community is expressing, in this case about diversity and inclusion, and to decide how to act to advance on diversity, equity, and inclusion.

CONCLUSION

A single article can only allow these authors to begin outlining where diversity and inclusion efforts should start. As shown, while women constitute more than half of the world's population, they are a much smaller portion of the scientific community and despite making important contributions to science throughout history, they also have consistently been unrecognized and underrepresented at all levels. This same pattern can be traced through the history of the Indigenous Communities, who constitute 5% of the population (UNESCO, 2022a) and who preserve 21% of Soil that we all need to survive (ICCA Consortium, 2021) and who are paid back with 15% (UNESCO, 2022a) of the world's poverty and whose presence in science is almost non-existing.

Gender equity data for soil science is extremely limited worldwide, and there are few scientific studies published on gender and indigenous communities within soil science. Shortage of specific information on gender equity in soil science indicates by itself both the lack of existing interest of soil scientists in this topic and that the gender gap is not recognized as a significant issue within the national societies of soil science. This equally is a reverse way of showing that the gender gap in soil science is real and that we need to work on it.

Closing the current gaps in diversity, equity, and inclusion that exist today in soil science are pending and essential tasks to be carried out urgently by our scientific community because to face the current environmental challenges, we require all the brains and hands working together -and not just half of them-, to achieve the sustainability of the soil resource as the essential element for life on Earth. Soil Science Societies will develop, implement, and monitor the adoption of a policy of equity, equality, inclusion, respect, and diversity for each other to close all the gaps.

We need to take down gender stereotypes that link science to masculinity, or that exclude racial backgrounds or similar identifying features and factors, we need to clearly show the new generations that there are great examples of researchers, engineers, technicians, and soil scientists from all genders and backgrounds.

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LBR-S and AI contribute with the conceptualization, data curation, formal analysis, investigation, project administration, resources, software, validation, writing-original draft, writing-review and editing.

CONFLICT OF INTEREST

AI is employed by John Wiley & Sons, Inc.

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Gender Equality in Soil Science in Italy: Wishful Thinking or Reality?

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Gender equality in Italian soil science is still far from being a reality although an in-depth investigation has never been carried out. In this work we analyse data on women soil scientists working in public research institutions and universities as well as on those affiliated with soil science societies, considering the changes in gender balance with time. We also recall three female pioneers in Italian soil science who played a key role in both research and scientific societies. An analysis of the impact of papers authored by Italian women is finally provided to gauge the contribution of Italian women to soil science in the last 20 years. The results show that the National Research Institutions reached a more equal balance between genders compared to universities. With regard to scientific societies, we observed a strong lack of female inclusion in the first years of the Italian Soil Science Society, founded in 1952, and the Italian Society of Pedology, even if it was founded much later in 1998. The Italian Society of Agricultural Chemistry was less discriminant, likely due to the presence of different sub-disciplines traditionally more open to women, although always far from real equality. With time, in all societies and research institutions we registered a positive trend with a better balance and a pro-active participation of women. However, we observed a persistent loss of highly qualified women resources from the training phase to the beginning of the career as well as under-representation of women in top roles and in the research centre leaderships. However, when we evaluated the scientific production, no statistical differences appear between women and men at all career levels, confirming the key contribution of women to soil science, despite facing major professional difficulties and disparities. These results show that, notwithstanding the marked progress in the number of women entering and working in Italian soil science, beyond the hard numbers, gender equality still remains a challenge and requires greater investments in resources and research toward structural and systemic interventions that may successfully lead to a more gender-balanced society.

Keywords: gender balance, Italian women in soil science, scientific societies, research institutions, authorship

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INTRODUCTION

Gender equality is among the Sustainable Development Goals of the United Nations, and in general, gender issues in society and at working places has been a hot topic in the last years in several countries all over the world. Discrimination in science was addressed as early as in 1983 (Acker, 1983), but still in the year 2000 the situation has not changed much as the scientific community was "shocked by revelations of sexual discrimination" arising from surveys conducted in Sweden and at MIT, United States (Loder, 2000). Recently, Dawson et al. (2021) more specifically examined gender equity in Soil Science in a number of countries. Italy was among those having a lower-than-average proportion of women affiliated to Soil Science Societies (27% with a worldwide average of 32%, and of 38% in Europe).

In Italy, the path towards the concept of equal opportunities began in 1945, later than in other countries (https://www.mappr.co/thematic-maps/women-rights-of-vote/), when, with the right to vote extended to all citizens without distinction of sex, the Constitution recognized equality for men and women. The Kingdom of Italy, in fact, ignored the female part that constituted it; for this reason in 1861, shortly after Italian Unification, the Lombard women, defining themselves as "Italian citizens," submitted to the Parliament a petition in which they claimed the right to vote, as they had before Unification, and asked for it to be extended to the whole country. However, only at the end of the Second World War was this right finally recognized.

The Italian Constitution consists of 139 articles and the gender issue is affirmed in three of them. Article 3 states: "a*ll citizens shall have equal social dignity and shall be equal before the law, without distinction of gender, race, language, religion, political opinion, personal and social conditions.*" Article 37 intervenes directly on women's work, stating that "*Women workers shall be entitled to equal rights and to equal pay as men for equal work. Working conditions shall allow women to fulfil their essential role in the family and ensure appropriate protection for the mother and child*". In Art. 51 one reads: "*Any citizen of either sex is eligible for public and elected offices on equal terms, according to the requirements established by law. To this end, the Republic shall adopt specific measures to promote equal opportunities between women and men*".

It took many years before laws were enacted accepting the provisions of the Constitution; it was indeed necessary to reform the previous family law and draft new legislation on the matter to eliminate, at the juridical level, the patriarchal conception of the family in favour of shared parent responsibility. Until the 1970s, legislation tended to "protect" women rather than sanction their equal opportunities; the interventions were aimed at safeguarding the rights of women whose condition continued to be in many respects lower than that of men.

With the right to vote for women in 1945, Italy anticipated the international legislation on this matter, which saw the affirmation of the principle of equal opportunities introduced in 1948, when the United Nations adopted the Universal Declaration of Human Rights. In Europe the problem relating to equal opportunities between men and women has been tackled since the 1960s with the drafting, decade after decade, of five action programmes. Among the European Union treaties relating to equal opportunities, it is appropriate to mention: the Maastricht Treaty (1993), (Art. 119) which established equal salaries between men and women for the same job, and the Treaty of Amsterdam (1997) which promoted "gender equality," combated gender discrimination, included women's rights among fundamental social rights and promoted the adoption of measures aimed at facilitating professional activities undertaken by women. Due to gender diversity, either for biological, social and cultural reasons, the term "equal dignity with respect to gender differences" is often preferred to "gender equality," with the goal of promoting equity, diversity, complementarity and inclusion as a necessary key for an effective fair socio-cultural and economic evolution of society.

Societal cultural evolution and the measures implemented by national and international laws have led to an increased presence of women also in the scientific community. Yet despite some encouraging signals, women are still underrepresented especially in leadership positions and in award rates in STEM disciplines (Sharma and Yarlagadda, 2022). According to UIS (UNESCO Institute of Statistics) data, female researchers worldwide constitute less than 30% of the total in 2016 (UIS, 2019). Appreciable differences exist between Western (39.3%) and Central-Eastern Europe (32.7%) with respect to the percentage calculated on total persons employed in R&D (research and development) in 2017 or the latest year available (UIS, 2019). At the European level, overall, 48.1% female doctorates (EU-27) were recorded in 2018, with an increase of about 1% over 2010 (EC DG RTD, 2021). Substantial differences persist among fields of studies, with a majority of women in Education, Arts and Humanities (66%), Social Sciences (56%), Agriculture (57%), Health and Welfare (60%), and a minority in the other fields, where the differences among genders are particularly high, i.e., in ICT (26%) and Engineering (29%) (EC DG RTD, 2021). The differences increase when permanent academic positions are considered, where women represent about 42% of the total academic staff, and where only 26% of them are employed at top positions (EC DG RTD, 2021).

Compared to Europe, in Italy, women represent about 40% of the total academic staff but only about 24% are at the highest positions (EC DG RTD, 2021). According to the Gender Balance reports periodically published by most of universities, the figures are different, according to local conditions, but recurrent: on average, PhD students, doctorates and post doc are more or less equally distributed by sex (Liccardo et al., 2019). The differences increase with permanent positions, where men are always more represented than women (EC DG RTD, 2021). Similar overall trends are reported for public research organisations, like the National Research Council (CNR) and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), with top positions largely occupied by male scientists (CUG ENEA, 2020; Avveduto et al., 2021).

Many reasons can be invoked to explain the Italian situation that, as detailed above, shows a slightly higher under-representation of women in both total academic staff and in leading positions. For example, French women researchers in a 2002 survey were found to take advantage of a good child-care system (Hermann and Cyrot-Lackmann, 2002). Italy is characterised by a lower level of family- and child-related policies than other EU countries (Bozzon et al., 2017), despite what stated in Article 37 of the Constitution, and care-giving is often perceived by women as a limitation in academic career (e.g., Preston, 2004).

Some recent papers address the specific gender conditions in soil science globally (Dawson et al., 2021), in the United States (Vaughan et al., 2019) and in land use sciences (Kamau et al., 2021). Updated analyses are also contained in de Vries (2017). The general conclusion agree on an under-representation of women in soil-related careers, especially in leadership positions. No published data are available about soil science in Italy, although the situation may be slightly different from that of other countries.

Soil Science in Italy is typically taught in agriculture-related university studies, i.e., in a field where women are well represented at the EU level, as reported above. Research in soil science however follows the methods of hard sciences, which are disciplines showing a systematically lower proportion of female students (e.g., Tandrayen-Ragoobur and Gokulsing, 2022).

For moving towards equality, diversity and inclusion in soil science, we need to know the gender balance at country level. So far, only a few studies exist. Beside the already mentioned in depth study for the United States (Vaughan et al., 2019), a recent paper deals with gender equality in soil science in Indonesia (Fiantis et al., 2022) connecting the women presence in soil science to soil security. No published data are available about soil science in Italy, although the situation may be slightly different from that of other countries.

This paper intends to provide a picture of the gender balance in Italian soil science and general recent trends, based on data retrieved from different sources: women soil scientists working in public research institutions and universities; women soil scientists affiliated to scientific societies; women publishing in soil related fields. An analysis of the impact of Italian women-authored papers is also provided to understand the contribution of Italian women to soil science in the last 20 years.

MATERIALS AND METHODS

A specific curriculum in Soil Science is not present in the Italian university system. Soil Science, and its sub-disciplines, are taught in faculties of Agricultural and Forest Sciences (mainly), Natural Sciences, Geology, Environmental Sciences, Environmental Engineering. Specific doctorate courses in Soil Science are given in some universities, but still some soil scientists hold a doctorate in Agricultural, Geological or Biological and Environmental Sciences. Defining a soil scientist is therefore an issue. Moreover, if researchers or professors working at university "state" their affiliation to a specific discipline, this does not apply to other research institutions. Therefore, we used different sources and methods as described in the following subsections.

Women in the Past of Italian Soil Science

The information about early Italian women soil scientists were retrieved from the Italian Society of Soil Science archives integrated with what is available on the web and with direct accounts from people who knew them, including the Authors of this paper.

University

Research staff in Italian universities are grouped into sectors that do not always correspond to ERC (European Research Council) sectors, as they are often more specific. Despite this specificity, Soil Science is embedded in two sectors: Pedology (AGR/14), and Agricultural Chemistry (AGR/13). As soil biologists are a minority and are included in different sectors such as Microbiology, Ecology and Entomology, they were not considered in this work. Some additional soil scientists are present in faculties of Earth Sciences and belong to other sectors. Also, in this case they are a minority within a much larger number of geomorphologists and quaternary geologists. While the Pedology sector (AGR/14) only includes soil scientists, that of Agricultural Chemistry (AGR/13) is bigger and also includes plant biochemists.

The data for the analysis were downloaded from the Ministry of University and Research (MUR) website (https://www.mur.gov.it/it), selecting the permanent staff belonging to sectors AGR/14 and AGR/13 in 2001, 2011 and 2021. No attempt was made to split the Agricultural Chemistry sector into soil scientists and plant biochemists, but this was taken into consideration when discussing the results. No suitable official data are instead available for PhD students or post-doc working at Italian universities.

Public Research Institutes

Soil research is also addressed in several Italian research institutions: National Research Council, CNR (www.cnr.it), Council for Agricultural Research and Agricultural Economy Analysis, CREA (https://www.crea.gov.it/), Italian Institute for Environmental Protection and Research, ISPRA (https://www.isprambiente.gov.it/), Italian National Agency for New Technologies, Energy and Sustainable Economic Development, ENEA (https://www.enea.it/) amongst others. However, traditionally, soil research has been mainly carried out in some research centres of CREA and CNR.

CREA, with over 1000 researchers, is the largest Italian research body dealing exclusively with agri-food topics; it is supervised by the Ministry of Agricultural, Food and Forestry Policies. CREA was established in 2015, from the merging of CRA (Council for Agricultural Research) and INEA (National Institute of Agricultural Economics) and is under the direct supervision of the Ministry for Agriculture (Gaudio, 2020). CREA is organised in 12 research centres (6 related to specific supply chains and 6 dedicated to horizontal topics) throughout the country. One of these centres is dedicated to Agriculture and Environment and Soil Science (CREA-AA). In this work, the analysis was based on data as reported in the Plan of Positive Actions (PAP) of CREA (CREA, 2021).

The CNR is the largest Italian public multidisciplinary research institution, with more than 8000 employees, more than half of whom work as researchers. The CNR is organised in seven broad disciplinary departments, and in about one hundred institutes. Soil-related disciplines are mostly addressed in the departments of Biology, Agriculture and Food Sciences (DiSBA), and of Earth System Sciences and Environmental Technologies (DTA), in different institutes and laboratories spread all over Italy. In the 1970s a large research project on soil conservation was launched by the CNR, involving many soil scientists from Academia and Research Institutions and paving the way for soil science growth in Italy (Calzolari, 2013).

In order to capture the presence of women soil scientists at CNR, a search was performed on the CNR intranet site, where publications are stored by researchers (restricted access source). As the repository has however been actively maintained by researchers themselves only in the last 10 years on a voluntary basis, the database might not be complete. The search was launched, using the word “soil” as a keyword within the title field. Only papers published in journals between 1980 and 2021 were considered. The resulting titles were manually checked for detecting the gender of the contributing authors and their h-index, considering only the names of people affiliated to the CNR. The specific competence of the contributing authors was not checked, in order to avoid biases. Therefore, false positive cases may have been included in the search; on the other hand, false negative cases were also possible. However, a homogeneous distribution of the errors was assumed between genders.

For permanent and still active researchers, the present career position was checked (I, II, or III, comparable to the university positions of full professor, associate professor and assistant professor, respectively), on the CNR site (http://www.dcp.cnr.it/DPUASI/) together with the institute and department of affiliation.

Scientific Societies

There are three scientific societies covering aspects of soil science in Italy: the Italian Society of Soil Science (SISS) and two academic societies, the Italian Society of Pedology (SIPe) and the Italian Society of Agricultural Chemistry (SICA).

The SISS was established 70 years ago, and its purpose is to promote the progress, coordination and dissemination of Soil Science and its applications, and to foster relationships and collaboration between its practitioners. For this reason, it has always included specialists and researchers of various backgrounds belonging to different academic societies and research institutes. Moreover, the SISS, as a full member of the International Union of Soil Sciences (IUSS) and the European Confederation of Soil Science Societies (ECSSS), collaborates with international soil science institutions with similar purposes or common programmatic aspects. The mission of the SISS is inspired by the statute of the IUSS (formerly International Soil Science Society) founded in Rome in 1924. Data on members were collected from the archives of the Society where the minutes of the general assembly and the composition of the executive board are stored considering the members affiliated in 2001, 2011, and 2021.

The SIPe is smaller and broadly corresponds to the Pedology sector at universities and research centres. Its purpose is to promote, support and coordinate studies and research in the field of Pedology and its applications. The SIPe was founded recently, in 1998, and the membership data were made available on electronic media. The search focused on active members in 2001, 2011, and 2021 and the percentages of women soil scientists, as well as time trends were calculated.

The SICA was founded in 1981 with the aim of constituting a point of reference for those researchers and scholars who operated in the vast context of chemical and biochemical disciplines applied to agriculture. The SICA embraces members whose interest is soil chemistry, plant biochemistry and physiology, food chemistry, waste recycling, and environmental chemistry. It broadly corresponds to the Agricultural Chemistry sector in academia and research centres. For this analysis, the membership data were made available on the society website (https://www.chimicagraria.it/index.php). Also in this case, our search focused on active members in 2001, 2011, and 2021.

Scopus Literature Search

A specific literature search was performed on Scopus for the years 2001, 2011, and 2021, separately. In order to capture all possible soil science sub-disciplines, and in analogy with the approach followed for the CNR, a simple search was launched, using the word “soil” within the article title field, limiting the search to “Italy” in the affiliation country field. Only Scopus articles were then considered, omitting conference papers, reviews, editorials, data papers and/or book chapters. For some more detailed analyses, only Q1 journals (i.e., top 25% of journals within a subject category) in the soil science category were considered, following the impact factor reported in Thomson Reuter’s Journal Citation Reports (JCR). Each resulting title was checked to detect the Italian contributing authors, i.e., affiliated to Italian institutions, omitting Italian scientists working abroad, and foreign authors occasionally affiliated to Italian institutions. Italian authors were checked and manually separated by gender. The first author’s gender was also checked. Only a limited refinement was performed on the retrieved articles, just in case clear evidence of “no soil science” content was found by checking the article contents. As noted for CNR, using the term “soil” for the search may return false positive and false negative cases. However, a homogeneous distribution of the errors was assumed between genders.

RESULTS AND DISCUSSION

Women in the Past of Italian Soil Science

The SISS was founded in 1952, but the first woman scientist was only elected to the SISS board in 1976. Despite the tiny minority, early women soil scientists played a major role in paving the way for young women to be introduced to Soil Science. We wish to remember three of them, involved in different roles and sub-disciplines, all of them pioneers in their activities: Enza Arduino, Linda Federico Goldberg, Antonia Huyzendveld Arnoldus.

Enza Arduino (1927–2005) was a soil scientist at the University of Torino from 1959 to 1997, when she retired. She was head of the soil chemistry area from 1974, although she became full professor and the director of the Institute of Soil Chemistry only in 1986, at the age of 59. She held an MSc degree in Chemistry and was so interested in soil mineralogy that she was appointed as the chair of the Soil Mineralogy Commission of the Italian Soil Science Society, and sat for years on the board of the Italian Group of AIPEA (Association Internationale pour l'Etude des Argiles). Her first works were about the heavy metal contents in soils, mainly from the quantitative point of view, but metals were soon linked to uptake by plants and to their transfer into surface waters. At the beginning of the 1980s, she was the promoter of a new field of studies at her university. Acknowledging that metal transfer into the biosphere or hydrosphere depended on soil properties, including mineralogy, meant that soil forming factors should play a determinant role when upscaling the results of lab experiment into the landscape. That was the beginning of a new way of thinking that may be obvious to many readers now, but was not so evident to several soil chemists in Italy at that time. She tutored many students and had many co-workers, men and women. Among those who she tutored, one woman has to be cited: Elisabetta Barberis, a soil scientist who was the dean of the Agricultural Faculty and later the vice rector of the University of Torino. Enza Arduino died in 2005, but maybe thanks also to her open mind, the majority of those working at the Soil and biogeochemistry unit of the University of Torino are women, in all positions, from full professors (2 women vs. 1 man) to PhD students.

Linda Federico Goldberg was the first woman president of the Italian Society of Soil Science (SISS) in the period 1984–1990 32 years after its foundation. Another 27 years were to pass before the next woman was elected SISS president (https://scienzadelsuolo.org/storia.php). In 1985 Linda Federico Goldberg, in collaboration with Enza Arduino, coordinated the production of the volume "Methods of soil chemical analysis" published by Edagricole. The text followed that coordinated by Tommaso Eschena in 1976 (the Normalized Methods of Soil Analysis published in the SISS Bulletin no. 10) and remained a reference until 1997 when a new edition "Series of analytical methods for agriculture" directed by Paolo Sequi was published. Linda Federico Goldberg in 1987 was admitted at the Georgofili Academy and until 2002 she was one of the few women in the Academy (no more than 5–6%). In the first 20 years of the 2000s, the trend at the Georgofili Academy changed with a growing number of women academics, but to date no woman has ever been elected President.

Antonia Huyzendveld Arnoldus (1942–2018) was born in The Netherlands, but she lived in Italy for most of her life. She graduated in pedology with Alfred Zink in 1973 with a thesis on soil surveys in southern Lazio. She continued to work in Lazio during her long career, producing the first detailed soil maps in that region which remained the only ones until the late 1990s. She was the first female pedologist of the Italian Society of Soil Science in the early 1980s, a founder of the Italian Association of Pedologists in 1992 and vice-president until 2000. She mostly operated as a professional pedologist, but she had several teaching contracts with the universities of Siena and Rome, and an intense research activity. Her major scientific interest was on pedo-archaeology, a discipline in which she was a real pioneer for Italy. She participated in dozens of archaeological surveys and published a long list of articles and reports. She had a profound knowledge of alluvial plains and their palaeo-geography in Lazio and Tuscany. She was an example for many young women pedologists, being capable of taking care of her children while continuing her field activities. She was an open-minded scientist, deeply aware of the importance of soil as the archive of earth and human history, well before the present general acknowledgment. We remember one of her statements: *Soil is the "living skin" of the earth. Apart from its basic social and environmental functions to produce and protect, it contains information, since part of Earth's and Man's history are recorded in the soil profile.*

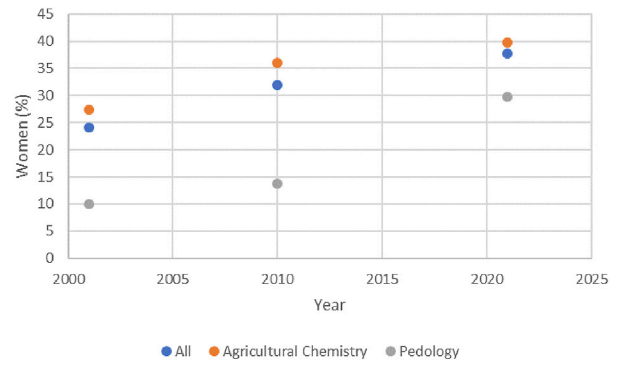

FIGURE 1 | Women (permanent staff) in Agricultural Chemistry and Pedology sectors in Italian universities.

University

In the last 20 years, the percentage of women scientists in the Pedology and Agricultural Chemistry sectors taken together has increased, from 25% in 2001 to 40%, in 2021 (**Figure 1**). The percentages are lower when only the Pedology sector is considered: women accounted for only 10% of scientists in 2001 and increased to 32% in 2021 (**Figure 1**). The increasing trend is encouraging, but when the career level is considered, the situation is very far from one of equality. As shown in **Table 1**, in 2021, only 26% of the full professors were women globally, but the percentage decreased to less than 15% in the Pedology sector. The well-known trend of a lower number of women at top positions was well visible, in all datasets and all years, confirming the vertical segregation mechanism highlighted in the Gender Balance reports published periodically by most universities and consisting of a persistent under-representation of women in senior management and governance bodies. The first female full professor in the Pedology sector appeared only in the most recent dataset, while women assistant professors were

TABLE 1 | Roles of women soil scientists at Italian universities in the last 20 years (N, number of scientist; only permanent staff).

University soil scientists	2001				2010				2021			
	Women		Men		Women		Men		Women		Men	
	N	%	N	%	N	%	N	%	N	%	N	%
Whole dataset												
Full Professors	7	14	44	87	8	20	33	80	9	26	26	74
Associate Professors	9	21	34	79	15	35	28	65	31	42	43	58
Assistant Professors	24	38	40	63	31	41	44	59	22	46	26	54
Total	**40**	25	**118**	75	**54**	34	**105**	66	**62**	40	**95**	61
Agricultural Chemistry												
Full Professors	7	17	35	83	8	24	25	76	8	29	20	71
Associate Professors	9	26	25	74	14	39	22	61	25	43	33	57
Assistant Professors	21	39	33	61	27	45	33	55	19	48	21	53
Total	**37**	29	**93**	72	**49**	38	**80**	62	**52**	41	**74**	59
Pedology												
Full Professors	0	0	9	100	0	0	8	100	1	14	6	86
Associate Professors	0	0	9	100	1	14	6	86	6	38	10	63
Assistant Professors	3	30	7	70	4	27	11	73	3	38	5	63
Total	**3**	11	**25**	89.3	**5**	17	**25**	83	**10**	32	**21**	68

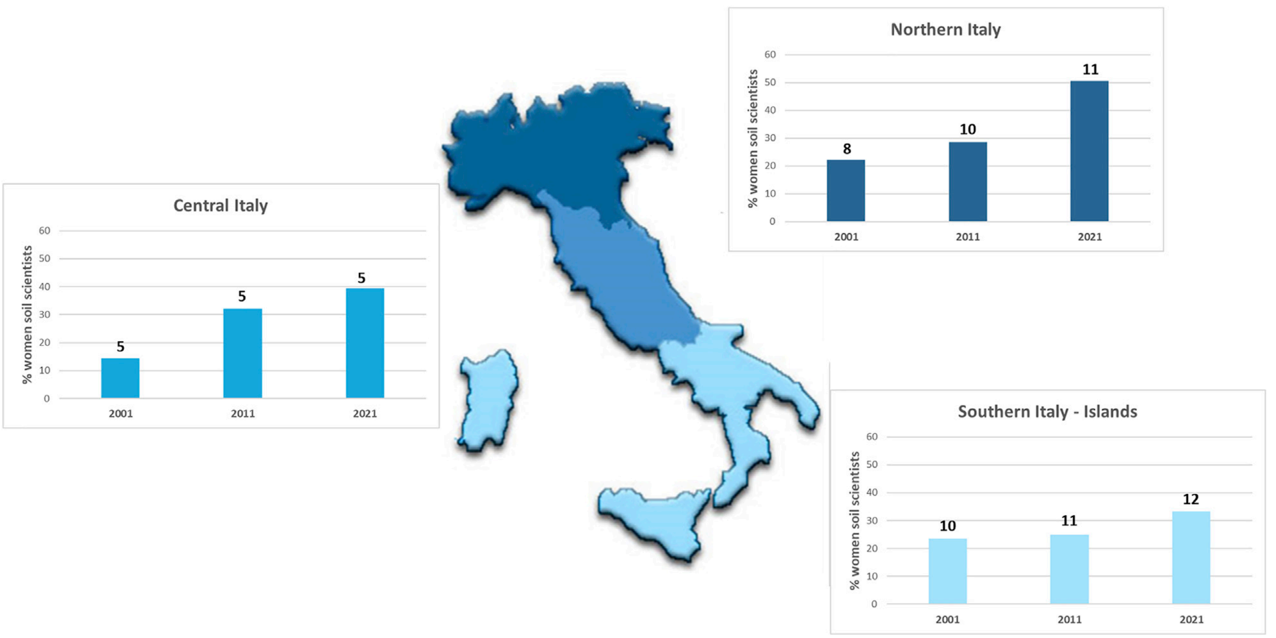

FIGURE 2 | Geographical distribution of the presence of women soil scientists at Italian universities in the last 20 years (only permanent staff). The number of universities are also reported for each year.

present already in 2001. The proportion of full professor women in Italy is 24% (in 2018, EC DG RTD, 2021), below the European average of 26%. This proportion decreases for Agricultural Sciences to 19% (28.50 for EU 27; EC DG RTD, 2021). If in Agricultural Chemistry the proportion (29%) is higher than the average of the Agricultural Sciences sector, the proportion for Pedology is much lower.

Women were (and are) equally poorly present at universities of all cities, with no specific geographic trend (**Figure 2**). Interestingly, in 2001 and 2011, when the groups were smaller, fewer women were present; where groups were formed by only 1–3 people women made up 5 and 9%, in 2001 and 2011, respectively (data not shown). The situation improved in 2021.

Public Research Institutions

Council for Research and Agricultural Economics

Our analysis highlighted a very important trend towards gender equality: out of the 1894 CREA employees 934 are currently males and 960 females. There is a slight prevalence of women in the profile of Researcher/Technologist (levels I-III, 407 women vs.

TABLE 2 | Roles of women in the CREA Research Centre of Agriculture and Environment (CREA-AA; N, number of scientists).

	Women N	Women %	Men N	Men %
CREA-AA researchers				
I level (full professor)	31	54	26	46
II level (associate professor)	3	60	2	40
III level (assistant professor)	3	43	4	57
All	37	54	32	46
CREA-AA techologists				
I level (full professor)	0	0	4	100
II level (associate professor)	1	33	2	67
III level (assistant professor)	7	54	6	46
All	**8**	**40**	**12**	**60**

Level I assimilated to Full Professor, Level II assimilated to Associate Professor, Level III assimilated to Assistant Professor.

TABLE 4 | Gender distribution of CNR soil scientists among the different career levels: Level I assimilated to Full Professor, Level II and Level III, assimilated to Associate Professor and Assistant Professor, respectively (N, number of scientists).

CNR all	Women N	Women %	Men N	Men %
I level (full professor)	11	33	22	67
II level (associate professor)	15	40	23	60
III level (assistant professor)	60	47	69	53
All	86	43	114	57

360 men). The male presence is predominant in the technical profiles (levels IV-VIII men 446 vs. 271 women). Women remain predominant in the managerial level of the Central Administration, although top positions are still mainly covered by men.

The specific data for the Research Centre of Agriculture and Environment (AA) in 2021 are reported in **Table 2**. As for CREA-AA, we do not have data for a temporal trend assessment. However, the present gender balance situation is much more balanced as compared to other research institutions and universities.

National Research Council

The search for publications on soil authored by CNR scientists was based on data available in the CNR intranet (restricted access). A total number of 1109 articles dealing with soil were published by CNR researchers between 1981 and 2021. In 633 of them at least one woman author was present (i.e., in 57% of cases). In the same period, CNR men were present in about 82% of cases. Women as lead authors represent 34% of cases (**Table 3**), and this percentage increases to 41% if single authors are counted only once. Considering the years 2001, 2011, and 2021, women were present in 46, 58, and 66% of the published articles, respectively, with an increase of 42% between 2001 and 2021. This trend is reflected by the women lead authorship which increased between 2001 and 2021 of 52% considering authors only once (13% as total).

Considering the whole time period, between 1981 and 2001, 461 male researchers published articles on soil, and 314 women researchers, i.e., 41% of the total (**Table 3**). Considering the years 2001, 2011, and 2021, the % of women scientists were 24, 43, and 47%, respectively, with an increase of 96% between 2001 and 2021 (**Table 3**).

Different professional figures contribute to CNR research activities, including technicians, PhD students, post doc researchers and temporary staff who are usually fully acknowledged among the authors. Limiting the analysis to working permanent research staff (excluding technicians, temporary staff and retired scientists), 219 soil scientists are currently working at the CNR (**Table 4**), of whom 86 are women (43%) and 114 men (57%). At level I (equivalent to full professor), which is the highest degree, women account for 33% of positions, while at level II (associate professor) and III (assistant professor) they represent 39.5 and 46.5%, respectively, highlighting again a discriminating difference in top positions.

Considering the h-indexes attributed to the research staff, we observed the trend reported in **Figure 3**. The average h-indexes recorded in Scopus did not differ between women and men in any of the professional levels, and accordingly with their role, the h-index increased from the level III to the level I (**Figure 3**). From these results, it clearly appears that, in contrast with a still unbalanced opportunity for career promotion, research quality is equally achieved by both genders at all levels.

Researchers publishing on soil topics were spread across all CNR departments, although they were more represented at the Department of Biology, Agriculture and Food Sciences (DISBA) and at the Department of Earth System Sciences and Environmental Technologies (DTA), which have soil and soil conservation topics within their missions. However, DISBA is more focused on Agricultural Sciences and DTA more on Earth and Environmental Sciences. Considering only researchers affiliated to these departments, we observed the trend reported in **Table 5**.

While in DTA the general distribution of genders at the different levels was comparable to (or higher than) the overall CNR staff (Avveduto et al., 2021), in DISBA the percentage of

TABLE 3 | Gender distribution of soil scientists affiliated to CNR in 2001, 2011 and 2021, as derived by soil science articles.

YEAR	N of papers	N of papers with Women	N of papers with Man	% Papers with Women	Women N	Men N	% Women	% Women as lead authors
2001	13	6	12	46	5	16	24	23
2011	45	26	34	58	33	43	43	47
2021	61	40	50	66	55	62	47	26
1981–2021	1109	633	905	57	314	461	41	34

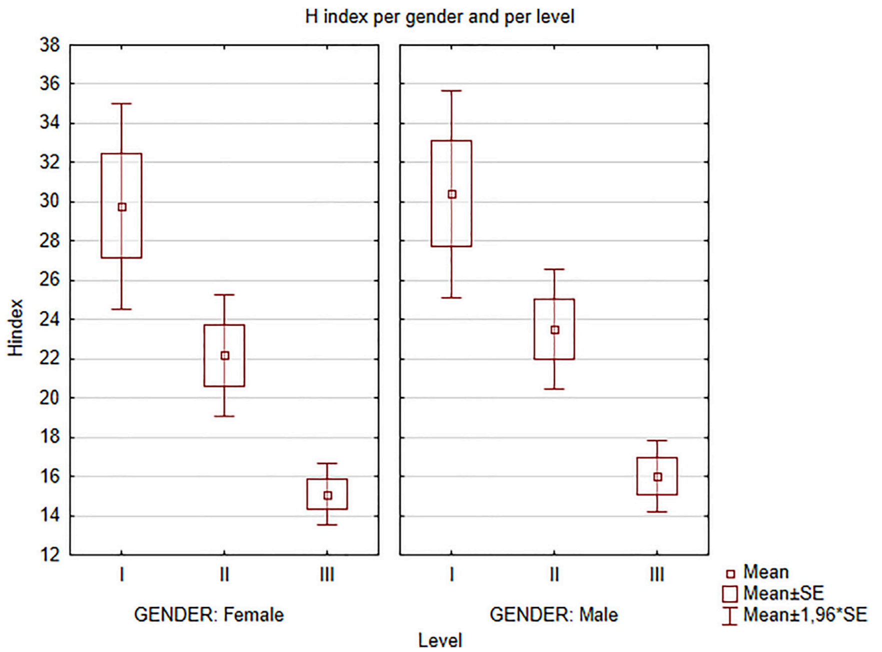

FIGURE 3 | Mean, standard error and confidence interval of scientists' H Indexes, for gender and career levels in the CNR. Level I = Full Professor, Level II = Associate Professor, Level III = Assistant Professor.

TABLE 5 | Gender distribution of CNR soil scientists among the different career levels in DISBA (Department of Biology, Agriculture and Food Sciences) and in DTA (Department of Earth System Sciences and Environmental Technologies).

	Women N	Women %	Men N	Men %
DISBA				
I level (full professor)	1	11	8	89
II level (associate professor)	9	47	10	53
III level (assistant professor)	20	44	26	56
All	30	41	44	59
DTA				
I level (full professor)	6	35	11	65
II level (associate professor)	5	36	9	64
III level (assistant professor)	26	48	28	52
All	37	44	48	56

women at the I level was considerably lower than the CNR average (Level I: 27 and 73% for women and men, respectively; Level II: 39 and 61%; Level III: 50.5 and 49.5%). Nevertheless, the average h-index, again, did not show any difference between genders at levels II and III (**Figure 4**).

Scientific Societies

The proportion of women affiliated to the Italian Society of Soil Science (SISS) increased from 21 to 33% from 2001 to 2021, with a slight decrease in 2011 (**Figure 5**). In 1952 the 14 founding members were exclusively male and only after 27 years did a woman join the society's executive board as the president of the commission III. However, it took as long as 32 years for a woman, Linda Goldberg, to become President of the SISS. Since then, the SISS registered a new trend with an ever-increasing presence of women on the board, due to both a general increase in total members and a more inclusive policy of the society. Female presence on the executive board was higher than the percentage of women in the membership, reaching an average of 30–35% in the 2020s, and, since 2017, and until present, SISS presidents have all been women! In this period, women also actively participated in innovation and evolution of SISS goals, expressing their great interest in the new SISS-connected institutions and organisations created to face the different soil issues arising over time.

The proportion of women affiliated to the Italian Society of Pedology (SIPe) showed steady data in the 3 years considered (**Figure 5**). Despite the presence in this dataset of PhD students and post-docs, women formed about 30% of the whole population. The SIPE board had long reflected the dominance of male soil scientists; the first woman on the board dates from 2004, reflecting the scarce abundance at both universities and research centres; the second joined in 2013 when women represented 20% of the board. This year (2022) however, the proportion of women is 50% and both the president and the vice-president are women soil scientists!

The proportion of women affiliated to the Italian Society of Agricultural Chemistry (SICA) was around 40% of the whole population in the 3 years considered (**Figure 5**). Since 1981, the year of SICA foundation, women have been a constant presence on the SICA board representing about 20%, mostly with the role of secretary-treasurer (5 out of 16) and board members (18 out of 64). This percentage has increased to 28% in the last 10 years. Nevertheless, the first woman president dates back to 2008, and the current vice-president, a woman, will become president in 2024!

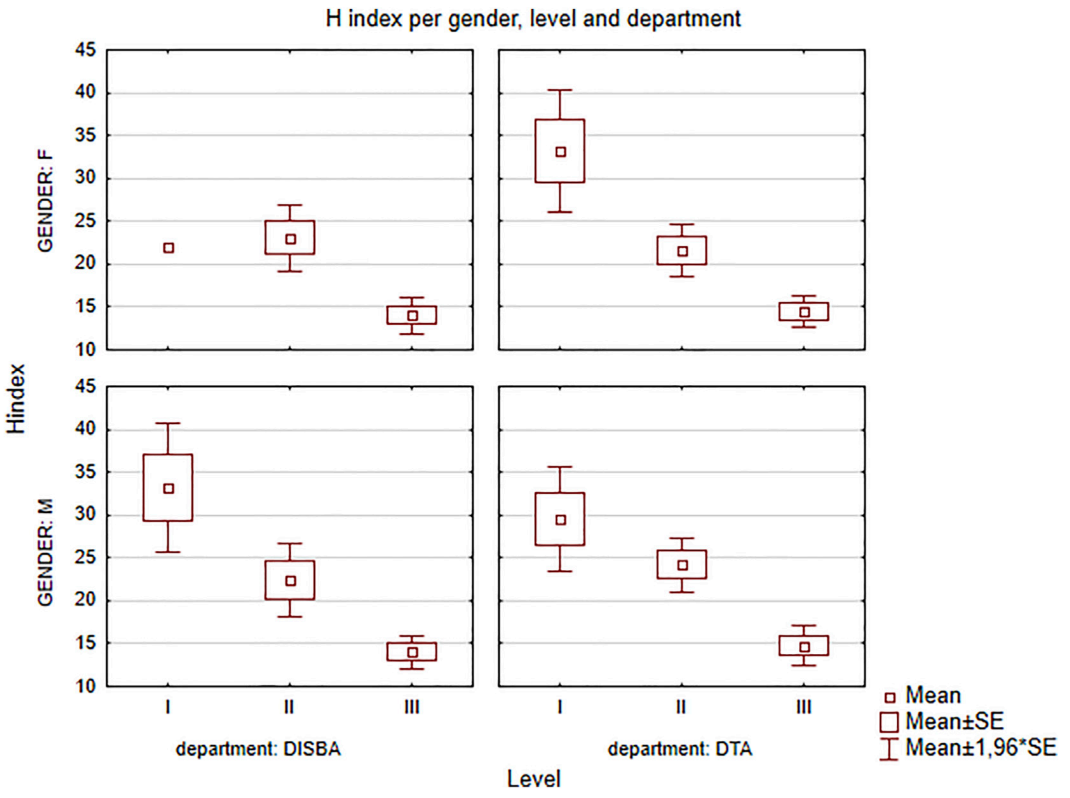

FIGURE 4 | Mean, standard error and confidence interval of scientist H-Indexes, for gender and career level in DISBA, Department of Biology, Agriculture and Food Sciences, and in DTA, Department of Earth System Sciences and Environmental Technologies: Level I = Full Professor, Level II = Associate Professor, Level III = Assistant Professor.

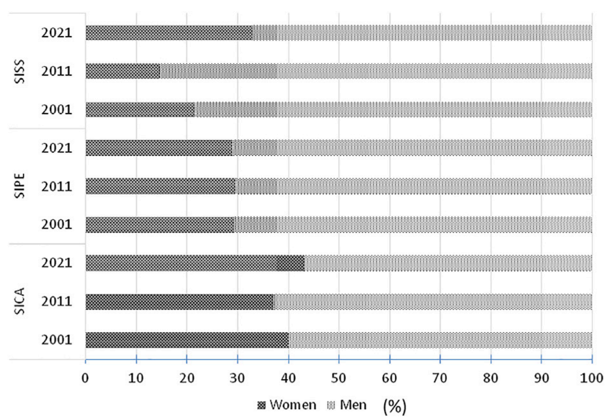

FIGURE 5 | Percentages of women and men affiliated to the Italian Society of Soil Science (SISS), the Italian Society of Pedology (SIPE) and the Italian Society of Agricultural Chemistry (SICA) in the last 20 years (2001, 2011, and 2021).

The percentages for the Italian soil societies are near to the global average of 32% of women soil scientists calculated over 44 soil science societies in 2020 (Dawson et al., 2021). Considering the European societies, whose average proportion of women is 38%, Italian societies are less gender balanced as compared to Baltic and eastern countries, which range from 36% to 69%, and interestingly also compared to Spain and Portugal (42% each).

Comparing these results, we could in general observe a still lower presence of women in universities, research institutions and soil scientific societies. Nevertheless, the recorded gender imbalance is not as high as the differences described in the ISTAT report (ISTAT, 2021), which shows a greater preference of men for hard science disciplines, such as Science, Technology, Engineering and Mathematics (STEM), with respect to women (37 % men vs. 17% women). This may however be related to the strong relationship between Agricultural studies and soil science in Italy, as stated above. Agriculture was indeed surprisingly among the sectors with the highest percentages of women in Europe (EC DG RTD, 2021). As a positive remark, we highlight an enhanced inclusion and pro-active participation of women in the three societies, progressively increasing with time, although only in the last 20 years has the number of women in leading positions been really significant. In general, the national research institutions have reached a greater gender equality compared to universities. With regard to scientific societies, even if the trend was generally positive, inclusion of women in the SISS was always lower as compared to SIPe and SICA. One reason could be that the SISS is the oldest Italian scientific soil society, while SICA and SIPe were founded in more favourable

TABLE 6 | Articles dealing with soil in Scopus in 2001, 2011 and 2021.

year	N articles	With W N	With W %	W/total %	W > M %	100% W N (%)	Women as first author %
2001	137	66	48	27	20	12 (9%)	34
2011	291	197	68	33	20	22 (8%)	42
2021	592	393	66	34	21	58 (10%)	43
All Groups	1020	656	64	33	21	92	41

N of articles, total number of papers considered for year; with W (N) and with W (%), number and percentage of papers with at least a woman; W/total %, percentage of women over the total of Italian authors; W > M %, percentage of papers with a majority of Italian women compared to Italian male scientists; 100% W (N) and (% in brackets), papers authored by only Italian women.

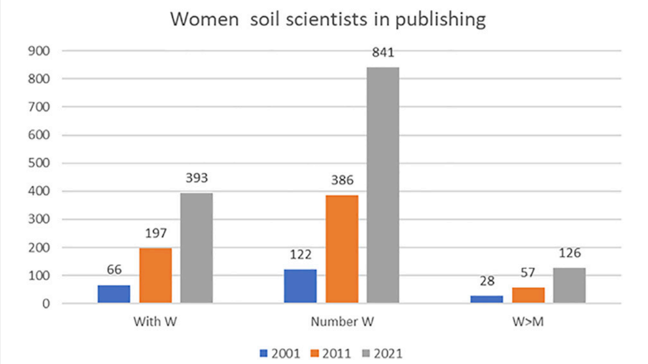

FIGURE 6 | Italian female presence in Scopus papers published in 2001, 2011, 2021 (only Italian authors are considered). With W (number of papers with at least one woman); Number W = number of women authors; W > M = number of papers with a prevalence of women.

periods for female inclusion with a faster trend towards gender equity. On the other hand, the SICA has shown the highest presence of women, probably due to a larger focus on soil chemistry and biology, that means more lab than field activities, with respect to, for example, pedology and soil hydrology.

Bibliographic Search

In all, 1020 articles were retrieved from Scopus dealing with soil to a certain extent and authored by Italian researchers (**Table 6**): 137, 291 and 592 articles published in 2001, 2011, and 2021, respectively. While in 2001 at least 48% of papers featured a female author, in 2021 this figure rose to about 66% of the total, with an increase of 38% in 20 years (but with a constant value since 2011). The percentage of women among the authors slightly increased with time, rising from 27% (122 Italian female authors) in 2001 to 34% in 2021 (841 Italian female authors; **Table 6** and **Figure 6**). However, the number of papers with a prevalence of women was more or less constant (21% on average, that is 28, 57, and 126 papers in the 3 years considered; **Figure 6**), as well as the percentage of papers authored by female scientists alone (9%, 8%, and 10%, in 2001, 2011, and 2021, respectively; **Table 6**). An increasing trend in the proportion of women as lead authors was also observed (**Table 6**): in 2001 the papers with an Italian woman as lead author were 38 (34 authors) versus 74 (64 authors) with an Italian man, with a proportion of 34%; in 2011 the proportion was 42% (92 and 128 papers, respectively lead by Italian women and men; 44% considering authors of multiple papers only once); in 2021 the papers with an Italian woman as lead author were 143 (125 authors) versus 186 papers lead by Italian men (168 individual authors) with a proportion of 43%.

Considering all the papers, the average citations per year and the Impact Factors (IF) of the journals considered in relation to the presence of female authors (**Figure 7**) were checked. A similar trend was observed between publications with at least one female scientist (series 1 on y axis of **Figure 7A**) and those without (series 0 on y axis of **Figure 7B**), although the number of citations of articles authored by at least one woman was slightly higher compared to the articles of only men (on average 3.9 and 3 citations per year, respectively). The articles where women authors prevailed over men (series 1 on abscissa of **Figure 7B**) showed higher average citations per year compared to articles with prevalence of men over women (series 0 on abscissa of **Figure 7B**): 5.4 and 3.0 citations per year, respectively. In both types of articles, those including at least one woman (**Figure 7A**) and those with a prevalence of one gender or another (**Figure 7B**), the average IF of the considered Journals did not differ. Moreover, different ranges of female author presence (0%, 25%, 50%, 75%, and 100%) were also considered to evaluate average citations and IF (**Figure 7C**). The average number of citations per year increased with increasing women presence (from 0 to 75%), reaching a maximum in correspondence of articles with 75% of women. However, differences among groups were not statistically significant.

For further analyses, only Q1 Journals with at least 10 records and with a publishing history covering at least 10 years were considered (**Table 7**): Applied Soil Ecology (ASE), Biology and Fertility of Soils (BFS), Catena, Chemosphere (CHEM), Environmental Science and Pollution Research (ESPR), European Journal of Soil Science (EJSS), Geoderma (GEODER), Journal of Hydrology (JoH), Science of the Total Environment (STOTEN), Soil Biology and Biochemistry (SBB).

In all, 167 articles were considered (**Table 7**). Articles authored by at least one female scientist were on average (calculated among all Journals) 71% of the total, with high standard deviation (46 on average), while the average percentage of women on the total Italian authors was 36%. On average, in 25% of cases women authors prevailed on men, and the calculated number of female authors per paper was 1.56.

Different trends may be observed among the journals (**Table 7**): Applied Soil Ecology showed the highest rate of articles with at least one female author (92%), the highest average number of women among the authors (average of

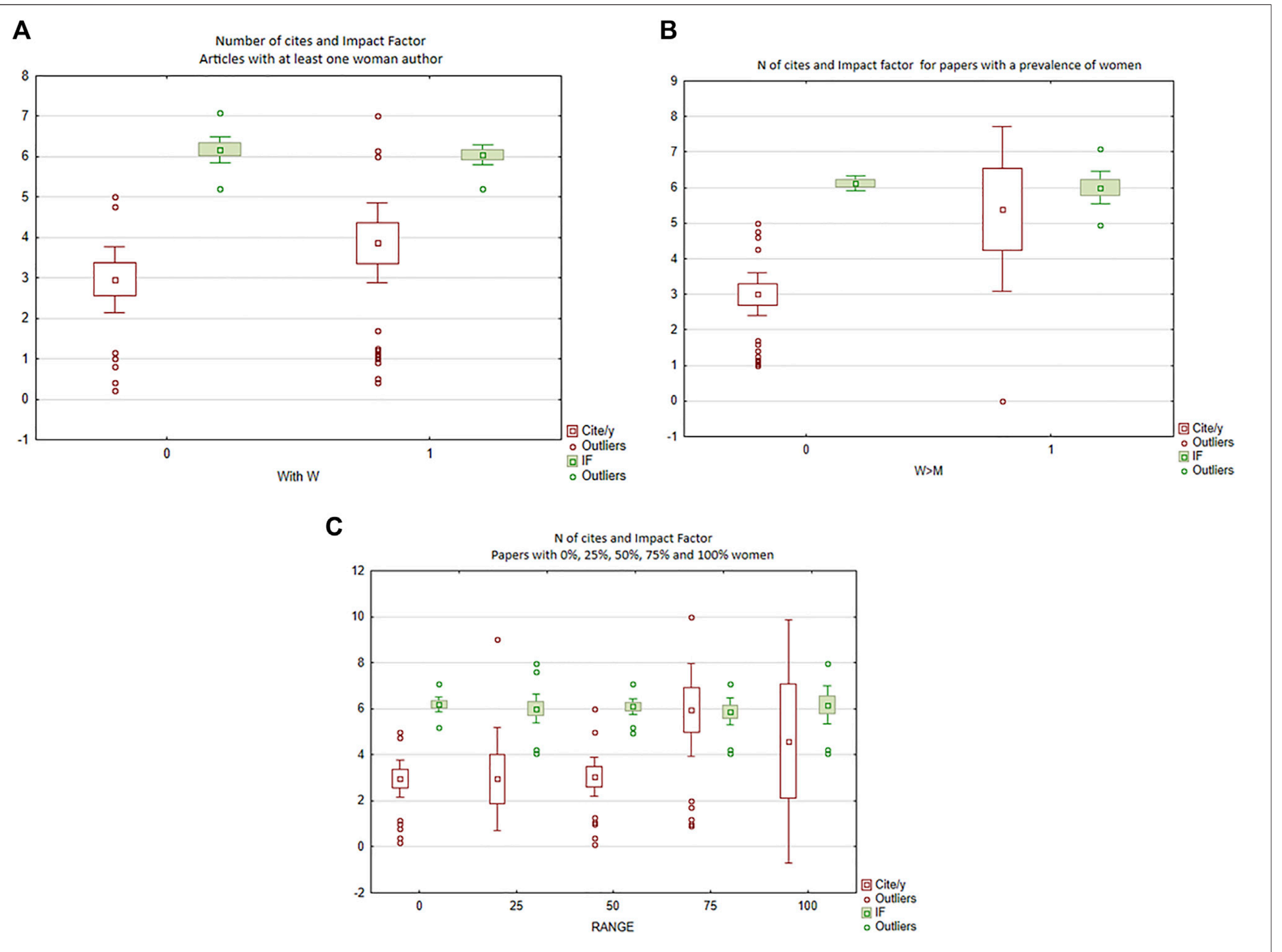

FIGURE 7 | Mean, standard error and confidence interval of citations per year and Journals impact factor (IF) for articles with at least one woman author **(A)**, for papers with a prevalence of women (1) or men (0) **(B)**, and for papers with 0%, 25%, 50%, 75% and 100% women **(C)**. Only Italian authors were considered.

TABLE 7 | Women authors in articles published in selected journals (Q1 and >10 articles).

Source	Total N	With W % (Means)	With W (Std.Dev.)	Ratio % (Means)	Ratio % (Std.Dev.)	W > M (Means)	W > M (Std.Dev.)	Number W (Means)	Number W (Std.Dev.)	IF
ASE	12	92	0.29	50.2	27.09	0.5	0.52	3.33	2.46	4.046
BFS	13	77	0.44	41.48	28.54	0.31	0.48	2.15	1.57	6.432
Catena	24	71	0.46	30.08	25.38	0.13	0.34	1.38	1.61	5.198
CHEM	14	86	0.36	45.6	31.9	0.36	0.5	1.86	1.41	7.086
ESPR	14	86	0.36	52.92	34.96	0.43	0.51	1.86	1.96	4.949
EJSS	10	60	0.52	25.5	32.51	0.2	0.42	0.8	0.92	4.223
GEODER	31	55	0.51	27.81	30.11	0.19	0.4	1.13	1.26	6.114
JoH	11	55	0.52	16.39	16.46	0	0	0.73	0.79	5.722
STOTEN	27	70	0.47	37.33	33.92	0.3	0.47	1.59	1.67	7.609
SBB	11	73	0.47	36.86	35.39	0.18	0.4	1.18	0.87	7.963
All Grps	167	71	0.46	35.65	31.05	0.25	0.44	1.56	1.63	6.083

Total N, number of papers per journal; With W % (mean, StdDev), mean N of papers with at least a woman (and standard deviation); ratio %, percentage of women scientists over the total Italian authors; W > M, ratio of papers with a majority of Italian female scientists as compared to Italian male scientists; Number W (means, StdDev), average number of women per paper (and standard deviation); IF, journal Impact Factor. Only Italian authors are considered. ASE, Applied Soil Ecology; BFS, Biology and Fertility of Soils; Catena; CHEM, Chemosphere; ESPR, Environmental Science and Pollution Research; EJSS, European Journal of Soil Science; GEODER, Geoderma; JoH, Journal of Hydrology; STOTEN, Science of the Total Environment; SBB, Soil Biology and Biochemistry.

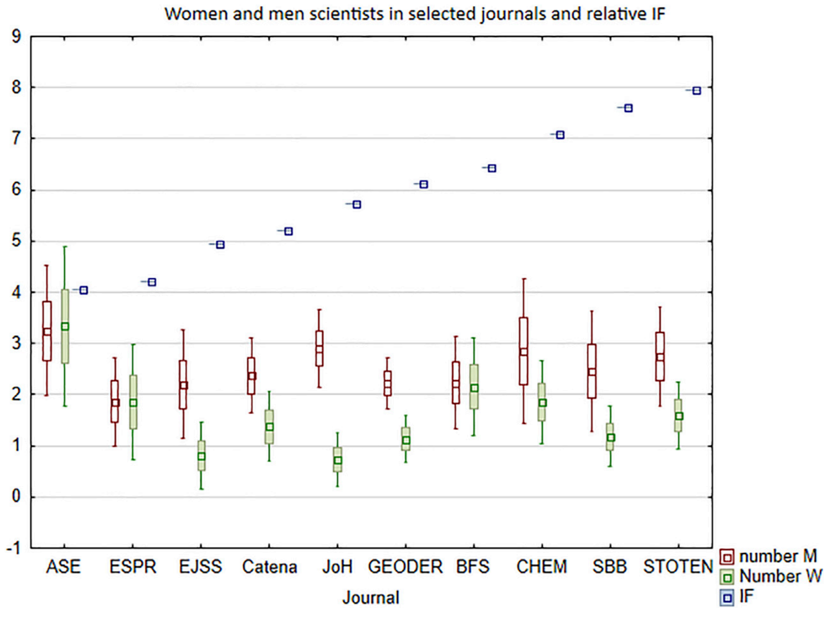

FIGURE 8 | Mean, standard error and confidence interval of number of women scientists (W), male scientists (M) in selected Journals (Q1 and >10 articles). The Impact factor (IF) of these journals is also reported. Applied Soil Ecology (ASE), Biology and Fertility of Soils (BFS), Catena, Chemosphere (CHEM), Environmental Science and Pollution Research (ESPR), European Journal of Soil Science (EJSS), Geoderma (GEODER), Journal of Hydrology (JoH), Science of the Total Environment (STOTEN), Soil Biology and Biochemistry (SBB).

3.3 women)—which was significantly higher than that found for the European Journal of Soil Science, Geoderma, Journal of Hydrology and Soil Biology and Biochemistry—and a higher rate of articles with a prevalence of female authors (50%). On the other hand, European Journal of Soil Science, Geoderma and Journal of Hydrology show the lowest rates for all the figures, below the mean values for all the chosen indicators.

The total number of women authors compared to men per journal is shown in **Figure 8**. Applied Soil Ecology, Biology and Fertility of Soils and Environmental Science and Pollution Research showed comparable numbers; a prevalence of men is recorded for all the other journals, and the differences were statistically significant for Geoderma and the Journal of Hydrology.

Chemosphere and Environmental Science and Pollution Research showed high scores for articles with at least one female author (86% each) and for the average percentages of women (46% and 53%, respectively). The other journals showed intermediate scores. It is worth noting that traditional soil science journals, such as the European Journal of Soil Science and Geoderma, still show a clear prevalence of male scientists. Catena, albeit with a more interdisciplinary and geomorphological approach, is also a reference journal for "pure" soil scientists. Also in this case, all indicators showed values below or near the overall average (**Table 7**). Women are better represented in journals with a focus on soil chemistry, and/or soil biology: Chemosphere, Environmental Science and Pollution Research, Applied Soil Ecology, Biology and Fertility of Soils and, to a certain extent Soil Biology and Biochemistry (**Figure 8**).

The Journal of Hydrology is aimed at hydrological sciences, with a prevalent engineering approach, a field where women are traditionally less represented (EC DG RTD, 2021). Science of Total Environment is a typical multi-disciplinary journal, with a great attention to innovative approaches. In this case, the presence of women is generally higher than the average (**Table 7**). With the exception of Geoderma (IF = 6.114), the journals with Impact Factor higher than average, Biology and Fertility of Soils (IF = 6.432), Chemosphere (IF = 7.086), Science of Total Environment (IF = 7.609) and Soil Biology and Biochemistry (IF = 7.963) recorded a good proportion of women among authors (**Figure 8** and **Table 7**).

CONCLUDING REMARKS

This work allowed to quantify for the first time in Italy and to show gender distribution differences in the national soil science community. Comparing the results obtained for the last 20 years, we highlighted an enhanced inclusion and pro-active participation of women, progressively increasing with time. In general, national research institutions have reached a more equal gender equality compared to universities. With regard to scientific societies, even if the trend has been generally positive, female inclusion in the SISS was always lower compared to the SIPe and SICA, probably because the SISS was founded before the other two societies. The highest presence of women in the SICA shows that some soil science sub-disciplines are more open to women (soil chemistry ~ biology > pedology ~ hydrology). That said, the presence of four women (out of six) as Presidents or Vice-Presidents of Italian soil science societies points strongly to the present and future active role of women. Indeed, when we move to evaluate scientific production, no statistical differences appeared between women and men at all career levels, confirming the key contribution of women to soil science, despite having often to tackle major professional difficulties and disparities.

In spite of the progressive gender equality in quantitative terms, only in the last 20 years has the number of women in leading positions been significant. Yet it is still far from constituting an effective equality: the increase in the number of active women in soil science is not yet reflected in career opportunities, as witnessed in both the CNR and universities. This leads to the loss of highly qualified female expertise from the training phase to career start, as well as the persistent under-representation of women in top roles and research centre leaderships, a well-known effect commonly referred to as the "leaky pipeline." (Blickenstaff, 2005). At universities, this phenomenon has become even more acutely expressed in recent years, probably because of the introduction of temporary research positions. This may have further amplified the dropping out of highly skilled women. The persisting imbalance in career advancement might also be related to an internationally documented difficulty for women to receive funds which adequately support their own scientific activity (Sato et al., 2021). The average research funding success rate at EU level, calculated as the number of beneficiaries of a research grant over the number of applicants, is on average higher for men (EC DG RTD, 2021). As for Agricultural Sciences, the research funding success rate differences between women and men in Italy is −9.03 as compared to an European average of 0.8 (EC DG RTD, 2021). However, we did not investigate in this article the Italian gender distribution in competitive projects due to the lack of consistent national databases. In addition, the Italian social system is still far from being an adequate and advanced structure, in which both women's private lives and careers may be equally favoured, removing obstacles which prevent full personal and professional equity, especially in the first steps of their scientific careers. In this context, university, as a training and research institution, should play a key role in targeting actions for overcoming the gender gap, by offering research-tailored solutions, as recently reported in a document published by the Ministry of Research and University (Addis et al., 2018). Any step towards greater inclusion, strengthening the differences as an added value and fully exploiting individual attitudes, skills and abilities, will lead to a more sustainable, fair and resilient society.

Thus, in answer to the opening question: "Gender equality in soil science in Italy: wishful thinking or reality?," although progress has undoubtedly been made in the number of women entering and working in soil science and in their role, a full equality remains an elusive goal and requires further investment in resources and research towards structural and systemic interventions that may successfully lead to a more gender-balanced society. Several authors suggest positive actions to be undertaken in order to actively promote gender equality (Brevik et al., 2021; Dawson et al., 2021; Fiantis et al., 2022), moving towards gender equity, intended as the recognition that different groups of people have different needs and need different resources and efforts to succeed. This includes identifying the obstacles specific to the career success of women and operating to remove them (Vaughan et al., 2019). With this paper a first contribution for the comprehension of the Italian situation in soil science was provided.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Brightness Values-Based Discriminant Functions for Classification of Degrees of Organic Matter Decomposition in Soil Thin Sections

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The decomposition of organic matter represents a fundamental pedogenetic process, since it impacts the carbon cycle and the release of nutrients to the soil. However, quantitative research aimed at micro-scale *in situ* analysis is scarce, despite its relevance in the decomposition process. Therefore, the objectives of this research were to generate discriminating functions of the degrees of organic matter decomposition, based on the brightness values associated with each morphological stage, and from this step, to generate thematic maps. Soil thin sections of forest and compost soils were selected, and petrographic microscope images with three light sources were taken: plane polarized light (PPL), crossed-polarized light (XPL), and crossed polarizers and a retardation plate (gypsum compensator) inserted (XPLλ). Subsequently, the RGB (red, green, blue) image was broken down into three bands, resulting in nine bands for each image. Two thousand sampling points were generated for each band, obtaining brightness values for each decomposed organic matter stage. The points were classified into four categories based on their degree of decomposition: no (A), light (B), moderate (C), and strong (D), in addition to porosity (P). Linear discriminant analysis was performed to obtain classification models for each level of decomposition. The results show that each degree of organic matter decomposition can be highlighted through specific light sources and a set of bands, with an overall accuracy of >94% and kappa coefficients of >0.75 for all classes. In addition, the resulting functions were validated in training images and high-resolution mosaics to create final thematic maps. The use of linear models automated the production and quality of thematic maps at the microscopic level, which can be useful in monitoring the organic matter decomposition process.

Keywords: linear discriminant analysis, micromorphometry, thematic maps, supervised training, variable selection

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INTRODUCTION

The decomposition of organic matter represents a fundamental pedogenic and pedomorphological process (Fanning and Fanning, 1989), where mineralization, humification, stabilization and melanization have been widely studied (Zech et al., 1997). Nevertheless, little research has been done at fine scale despite its importance in particle stabilization (Brzychcy and Zagórski, 2010).

Soil micromorphology describes organic components at microscopic level using undisturbed soil samples (Bullock et al., 1985); nonetheless, their description is complex because their characteristics change swiftly during the decomposition process (Stoops, 2003). Colour, opacity, and birefringence are some criteria used to characterize the subtypes of organic components (Bullock et al., 1985; Stoops, 2003); these criteria however, may be subjective with quantification since the decomposition of organic matter is a diffused-nature feature rather than a discrete feature (Bullock et al., 1985).

Image analysis of soil thin sections to study different soil components (Protz et al., 1992; Terribile and Fitzpatrick, 1995; Taina and Heck, 2010; Brzychcy et al., 2012; Jangorzo et al., 2014; Gutiérrez-Castorena et al., 2018) has been an adaptation based on remote sensing techniques (Protz et al., 1987; Ringrose-Voase, 1991; Protz and VandenBygaart, 1998). These routines have made it possible to eliminate the subjective description of soil thin sections (Skvortsova and Sanzharova, 2007), allowing better understanding of soil morphological process and their impacts on processes at greater geographical scale, such as ecosystems resiliency and adaptation, among others. In spite of that, the study of organic components and their dynamics at microscale has been little addressed, due to the complexity of their features (Poch 2015), and as a result of the changes that occur within the humification process in a relatively short period of time (Stoops, 2003).

Gutiérrez-Castorena et al. (2018) proposed to use the brightness levels of organic components from composite (RGB) images. This method provided a gain of information; yet it requires an elaborate and complex image processing routine. Other authors (Ringrose-Voase, 1991; Marschallinger, 1997; Terribile et al., 1997) have therefore, proposed the use of multivariate techniques when complexity is associated with the identification of soil components. One of these multivariate techniques is Linear Discriminant Analysis (LDA), which allows selecting, reducing variables, and generating classification models (Mika et al., 1999; Brown and Wicker, 2000; Hallinan, 2012). In addition, through the application of LDA it is possible to choose the best light source, band or set of bands handling visible light compositions (RGB) that present the highest sharpness and contrast of the organic feature. The hypothesis was: "since each image consists of pixels associated with a numerical value, it is also possible to create models to produce thematic maps using brightness values, and to quantify the organic features produced during the different stages of organic matter decomposition at microscopic level.

Therefore, the objectives of this research were: to generate linear discriminant functions based on the brightness values of each level of organic matter decomposition and to produce thematic maps at the microscopic scale in individual images and high-resolution mosaics of the whole soil thin section.

MATERIALS AND METHODS

The methodology used in this research consists of six steps, as illustrated in **Figure 1**.

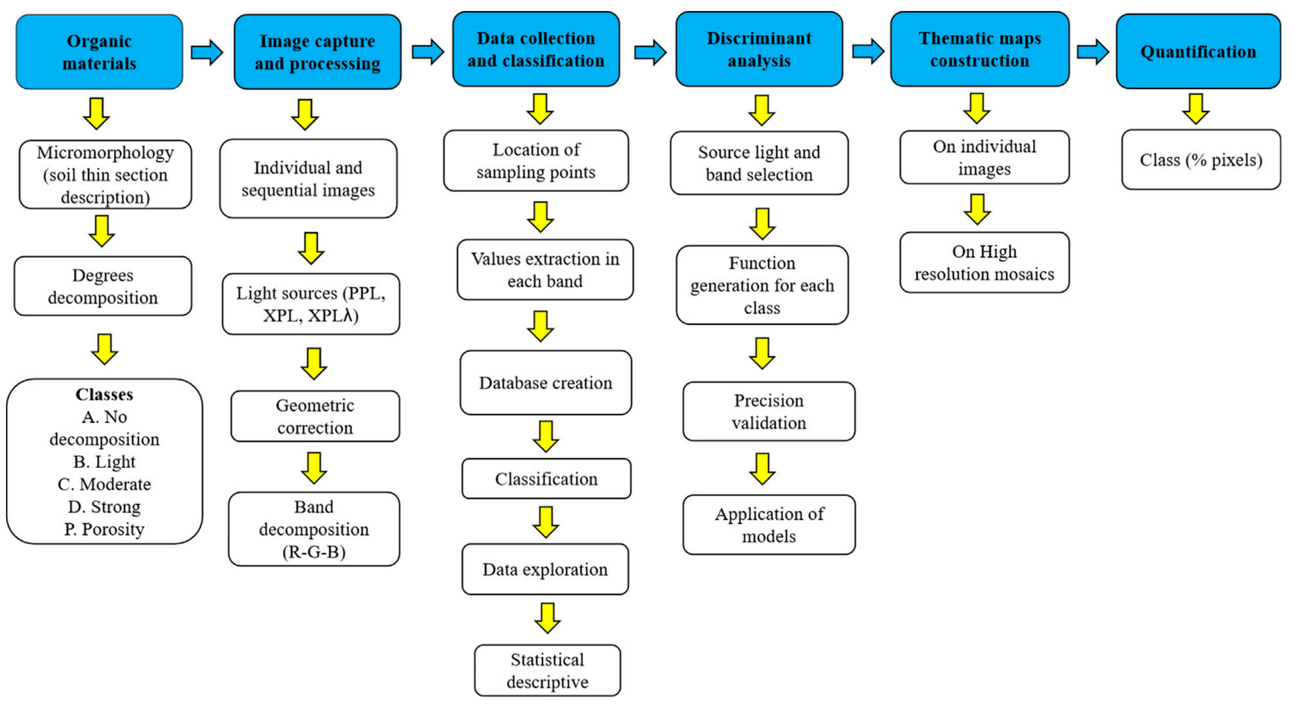

FIGURE 1 | Flow diagram of the procedure developed in the investigation. PPL = Plain polarized light; XPL = Cross-polarized light; XPLλ = Cross-polarized light with gypsum compensator. R = Red, G = Green, B = Blue.

Organic Materials and Their Micro-Morphological Description

We selected twenty soil thin sections corresponding to various surface horizons (O and H) of two soil classes (Andosols and Histosols) across the Valley of Mexico, plus one obtained from composting and vermicomposting material, to quantify various features of organic materials we wished to study. The description of the organic components of the sections studied is reported in **Table 1**. The description of organic components with different degrees of decomposition was based on their colour, internal structure and opacity in PPL, and birefringence and isotropy in XPL, according to the terminology proposed by Bullock et al. (1985) and Stoops (2003). Consequently, four classes were established: A) Not decomposed (internal structure and birefringence); B) Light (internal structure and birefringence), C) Moderate (internal structure, opacity, and isotropy), and D) Strong (opacity and isotropy); in addition, a category corresponding to the porous system P (transparency in PPL and isotropy in XPL) was added, as reported in **Table 2**.

Image Capture and Processing

In each soil thin section, single digital images (6) or digital sequential images (20) were taken to build high-resolution mosaics. All images

TABLE 1 | Description of Organic Components in different soils and composts.

Soil/compost	Description
Andosol	Abundant *Cupressus* sp. leaves, reddish-brown on inner tissues and dark brown on epidermis; opaque in XPL; moderate preservation. Common leaf controns, moderate to strong decomposition. Few fine roots, light brown in PPL and birefringent in XPL, moderate preservation. Few microaggregates and few reddish brown hyphae. 65% porosity. Fine, common excrements of mite (Oribatid). 65% porosity. Monte Tláloc, Texcoco, Mexico.
Acrisol	Plan residues of *Pinus sp.*; moderate to a strong degree of preservation needles residues; abundant leaf comminuted; abundant coarse contours with a high degree of decomposition; coalescence and abundant fine excrements of mites; abundant actinomycetes. Oaxaca, Mexico.
Andosol	Roots and tissues residues (parenquimatic, and lignified tissues), moderate preservation; fine organic material (cell residues, spores, and hyphae), and amorphous fine material. Coarse, and well-preserved roots and fine common contours; few charcoal residues; few excrements. Texcoco, Mexico.
Organic amendments	Frequent, moderate to strong degree of preservation of organ and tissues of vegetables and fruits (oranges, nopales, lettuce leaves, etc.); common organ and tissues fragments; few well-preserved roots; common organic fine material (spores); common fine and medium excrements; 35% microaggregates. Anthrosol, Texcoco.
Histosol	Frequent, medium to coarse, well-preserved roots; abundant, strong decomposition of tissue fragments; amorphous fine material. Glacier area (H horizon). Iztaccíhuatl, México.
Compost	Maize: Coarse stalk fragments; light brown in PPL and first order white interference colors in XPL; good to moderate degree of preservation.
Initial stage	Manure: Fragments of organ and tissues of alfalfa, moderate degree of decomposition, and moderate degree of preservation. Ratio 6:1.
Vermicompost	Vermicompost from grass pruning (*Cynodon dactylon*); good preservation; light yellow in PPL, and white in XPL. Tissues show first-order birefringence, primary fluorescence. The internal structure is complete. Few coalescence excrements. Nuevo Leon, Mexico.
Vermicompost	Vermicompost from bovine manure. Vegetable residues with a high degree of crumbling and alteration that has led to the formation of aggregates of subangular blocks, so there is no longer recognition of the original structure; dense coalescence excrements. Nuevo Leon, Mexico.
Vermicompost	Vermicompost from residues of sorghum (*Shorgum bicolor*). Vegetable residues with a high degree of crumbling and alteration that has led to the formation of aggregates of subangular blocks, so there is no longer recognition of the original structure. The degree of decomposition is mainly moderate; dense coalescence excrements. Nuevo Leon, Mexico.
Andosols	Plant residues of *Cupressus* sp and *Pinus* sp. Abundant reddish-brown controns of leaves and aciculae, moderate preservation. Fine to medium roots well preserved, 5% carbon residue; few, medium porous excretions; cell fragments common; moderately preserved. 15% microaggregates. Tlaxcala, Mexico.

TABLE 2 | Optical properties of organic matter decomposition levels for each light source.

Class	PPL			XLP		XPLλ
	Colour	Opacity	Internal structure (%)	Birefringence	Isotropy	Colour
A. No decomposition	Light brown	—	75–100	***	—	Light brown
B. Light	Yellowish brown	—	50–75	*	—	Yellowish brown
C. Moderate	Reddish brown- dark brown	**	25–50	—	***	Reddish brown
D. Strong	Dark brown-black	***	—	—	***	Black
P. Porosity	White	—	—	—	***	Pink

Low, ** Medium, * High.*

in the raw format (*.CR2) were captured from digital camera (Canon Rebel) mounted on a petrographic microscope (Olympus BX51). The images were obtained with a ×2 magnification on exposure of three light sources: plain polarized light (PPL), crossed-polarized light (XPL), and gypsum compensator (XPLλ). Each single digital image had a resolution of 1840 × 1,093 pixels, in RGB colour composition (24 bits); meanwhile the mosaics had 9,159 × 4,361 pixels. Therefore, the pixel size (spatial resolution) was approximately 10^{-2} (0.01388) mm. In addition, with sequential images, high-resolution mosaics were constructed using the procedure described by Gutiérrez-Castorena et al. (2018).

Image processing was carried out using the procedure described by Gutiérrez-Castorena et al. (2018). First, the images obtained in raw format were transformed to BIP format (24 bits) with extension.TIFF; then a resampling was performed using a bilinear interpolation method, and the original image dimension was transformed to the field of view of the microscope (11.9 × 7.46 mm) with a pixel size of 2.6 μm^2. Subsequently, the images were clipped to remove dark corners generated by the concave lens of the microscope. The final image size was 1,840 × 1,093 pixels, corresponding to a field of view of 9.2 mm × 5.47 mm. Finally, the digital images in each light source were rectified to achieve pixel-level overlap and broken down into its three components (R-G-B), acquiring a total of nine for each image (**Figure 2**).

Data Collection and Classification

Of the total of the individual images obtained, four were selected that had the maximum representativeness of each class and the highest quality in their elaboration, i.e., no birefringence caused by strain in resin. Then, 20 training fields were created, each consisting of 100 points, giving a total of 2,000 training sites for all images (**Figure 3**). For each training site, the brightness values of each of the nine bands were obtained using the "Extract values by points" routine of ArcGIS v.10.3 software. (Environmental Systems Research Institute, 2015). Each training site with its respective brightness values was classified (A, B, C, D or P). The 2,000 points included mainly organic components; however, in some thin sections there were also inorganic components. Therefore, their removal was necessary to obtaining the organic material models. Consequently, a raster database was built with 1,511 points bearing 13,599 point-data.

Dataset Preparation for Binary Classification

Five replicas of the original database were created to obtain the discriminant functions for binary classification, one for each level of decomposition and porosity. A cell reclassification was carried out in each database, which involved changing the class column; for example, Class A was changed to a value of 1 and the rest of the classes to values of 0 classes, producing binary classifications. Subsequently, the data set of each database was randomly divided into two: 80% to train the models and 20% to validate them according to the recommendations of James et al. (2013).

Separability between binary classes was performed using scatter diagrams with R version 3.5.3 (R Core Team, 2017) for each class analyzed, using the ggplot2 package. In addition, the minimum and maximum values of each class were evaluated to establish their ranges. If the scattergrams showed overlap between the binary classes, the points were reclassified and assigned values of 0; this process was called data cleaning, also known as data cleanse or data purge.

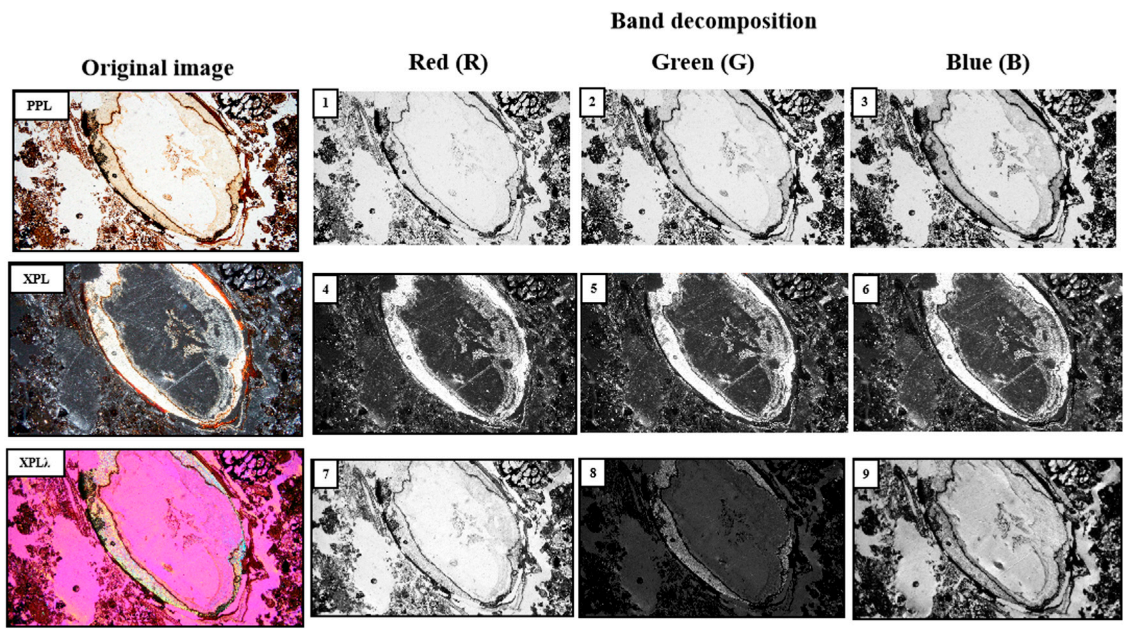

FIGURE 2 | Light sources decomposition to obtain the bands (RBG). Image length 0.9 mm. PPL = Plain polarized light; XPL = Cross-polarized light; XPLλ = Cross-polarized light with gypsum compensator.

Linear Discriminant Analysis and Estimation of Accuracy

Linear discriminant analysis (LDA) was carried out on the training fields of each database, using R v.3.5.3 through the MASS (Modern Applied Statistics with S) package and resulting in nine coefficients. The highest brightness values were selected from these coefficients, and a constant and a centroid were generated for each equation. According to Brown (2000), centroids are the mean of the values of the group members in a given discriminant function.

Kappa coefficient criterion to assess the classification (user's and producer's accuracy) of the reliability of the models were used according to Story and Congalton (1986) and Jensen (2015) proposals. The confusion matrix was carried out using the predict and confusion matrix functions of the caret and lattice packages of R v.3.5.3.

Construction of Thematic Maps and Quantification of Organic Features

The discriminating functions were applied to the images from which training fields were obtained, the individual images, and the mosaics, all this to execute the validation process of such discriminant functions. This procedure was performed with the ArcGIS raster calculator v.10.3, in which the selected bands in the LDA were multiplied by the coefficients of the generated

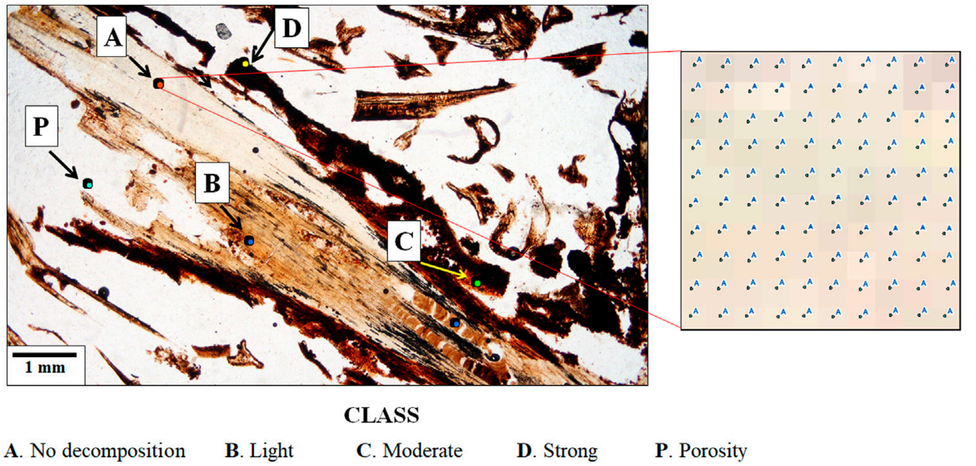

FIGURE 3 | Location of training sites for the degrees of decomposition of organic matter. The arrows indicate the sampled points. The box on the right represents a site with 100 sampling pixels in PPL. The image corresponds to forest soil, Acrisols, Oaxaca, Mexico.

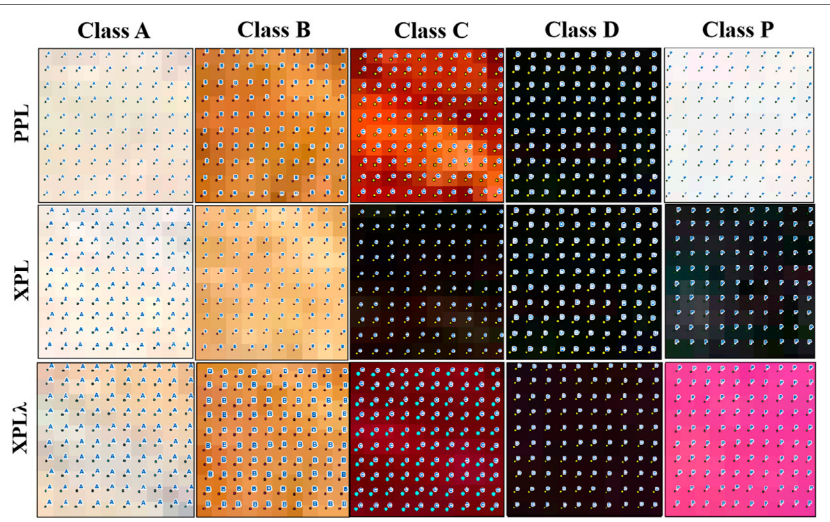

FIGURE 4 | Representative colours of composite images (RGB format) of different light sources and each degree of decomposition of organic matter. (A) No decomposition; (B) Light; (C) Moderate; (D) Strong, and Porosity (P).

discriminant function. After running the models in ArcGIS, a raster map was obtained showing classes of varying degrees of organic matter decomposition.

Finally, the quantification of each class was carried out by obtaining the percentage of pixels with respect to the total image.

RESULTS

Colour of the Degrees of Decomposition of Organic Matter

Figure 4 shows the representative colours of the five classes evaluated with different light sources, in which it can be observed that there is better separation of colours between PPL and XPLλ; while in XPL, there is confusion in three classes (C, D, and P) as a result of the isotropy of all materials. It is also shown that classes A, B, and D have some colour homogeneity regardless of light; class P contrasts in all light sources.

Degrees of Brightness

Figure 5 shows an overlap in brightness values between some classes when analyzing the original values, ranging from minimum (Class A, C, D, and P) to evident (Class B). However, with the re-categorization, the brightness values intervals were modified. For example, in class B, with less 30% modification, the brightness values of the intervals were reduced from 49 to 215 to 77–157 (green band in PPL) and from 17 to 177 to 17–79 (blue band in PPL) as it can be seen in **Table 3**.

Discriminant Functions

Each class studied with the linear discriminant analysis has specific lights and bands where the feature was characterized due to its increased sharpness and contrast (**Table 4**). For example, because by the type of light, the non-decomposed organic matter (Class A) stands out better in XPL (birefringence); whereas, the totally decomposed organic matter (Class D) is best identified (opacity and isotropy) in PPL. With XPLλ, the function coefficients obtained from LDA were low, and therefore were not further analysed.

As for the bands, the green (G) is helpful for all classes, the blue (B) gives good results in classes A, B, and C (up to moderate decomposition) and the red (R) only in class D, when the organic matter (OM) is strongly decomposed. Of the nine original variables, only two or three bands of the PPL and XPL were used to generate the models.

Accuracy of Models

The overall accuracy of the models was greater than 94% for Class A, C, D, and P and 89.1% for Class B. The accuracy increased by almost 5% for Class A and up to 6% for Class B, when data cleanse is applied to the training data set (**Table 5**).

Producer´s accuracy was for classes A, B, and C of 97.6%, 75.9%, and 87.3%, respectively, and for class D and P of 100%. After cleaning the data, the accuracy was increased, especially for class B (>22%). However, in user´s accuracy, percentages were lower for all classes when compared to those obtained in producer's (70.7%–98.3%); furthermore, after data cleansing, most percentages decreased (up to 8%), except for class A, which increased 11%.

The kappa coefficient obtained values ranged from 0.66 (Class B) to 0.99 (in the rest of the classes). After the data cleanse was applied, the values were irregular.

Application of the Model, Extraction of Features, and Creation of Thematic Maps

When the discriminant function was applied with the new pixel values, grayscale images were generated, where the class of interest was highlighted in a lighter shade compared to the other classes (**Figure 6A**). Subsequently, the layers were extracted (**Figure 6B**) and joined together to generate the thematic map of the different degrees of organic matter decomposition (**Figure 6C**).

Figure 7 shows the maps generated in individual images, and **Figure 8** shows the maps constructed from high resolutions mosaics where it can be seen that there is no clear division in classes A and B (without slight decomposition).

Quantification

The percentages of the objects classified in raster format agree with the visual analysis; however, in most training images, an overestimation was found in several classes as the percentages exceeded 100%. On the other hand, with the validation images, the percentages were less than 100% in most cases (**Table 6**).

As mentioned above, a "subclass" was presented in the images, which could not be classified with this method. This subclass was identified as the transition between non-decomposed materials and those with slight decomposition. Therefore, if the percentages are below 100%, this class was present in the image.

Analysis of Thematic Maps

The resulting thematic maps (**Figure 8**) show the distribution at microscale, of the varying degrees of decomposition of organic matter in the topmost layers of several soils and composting materials. These maps only highlighted the organic feature, no other features were highlighted except for the void; therefore, no associations could be identified with other pedofeatures, at this present time. However, it is safe to assume that material with relatively higher degrees of composition were closer to the proximity of voids (**Figures 8D,F**), since these materials are more exposed to decomposing agents; in contrast to materials relatively farther from the voids, which presented lower degrees of decomposition. In addition, the distribution of these stages followed a gradual pattern, that is, classes A and B, or classes C and D, would cluster together more frequently (**Figures 8B,D**), than classes A and C or classes B and D (top right of **Figure 7**). The occurrences of clusters of class A with classes C and D can be explained as abrupt displacements of materials due to water flow or faunal activity. Finally, no inferences could be made between degrees of organic matter decomposition with size of voids, suggesting the decomposition process of organic occurs independently of the size of voids within the soil fabric.

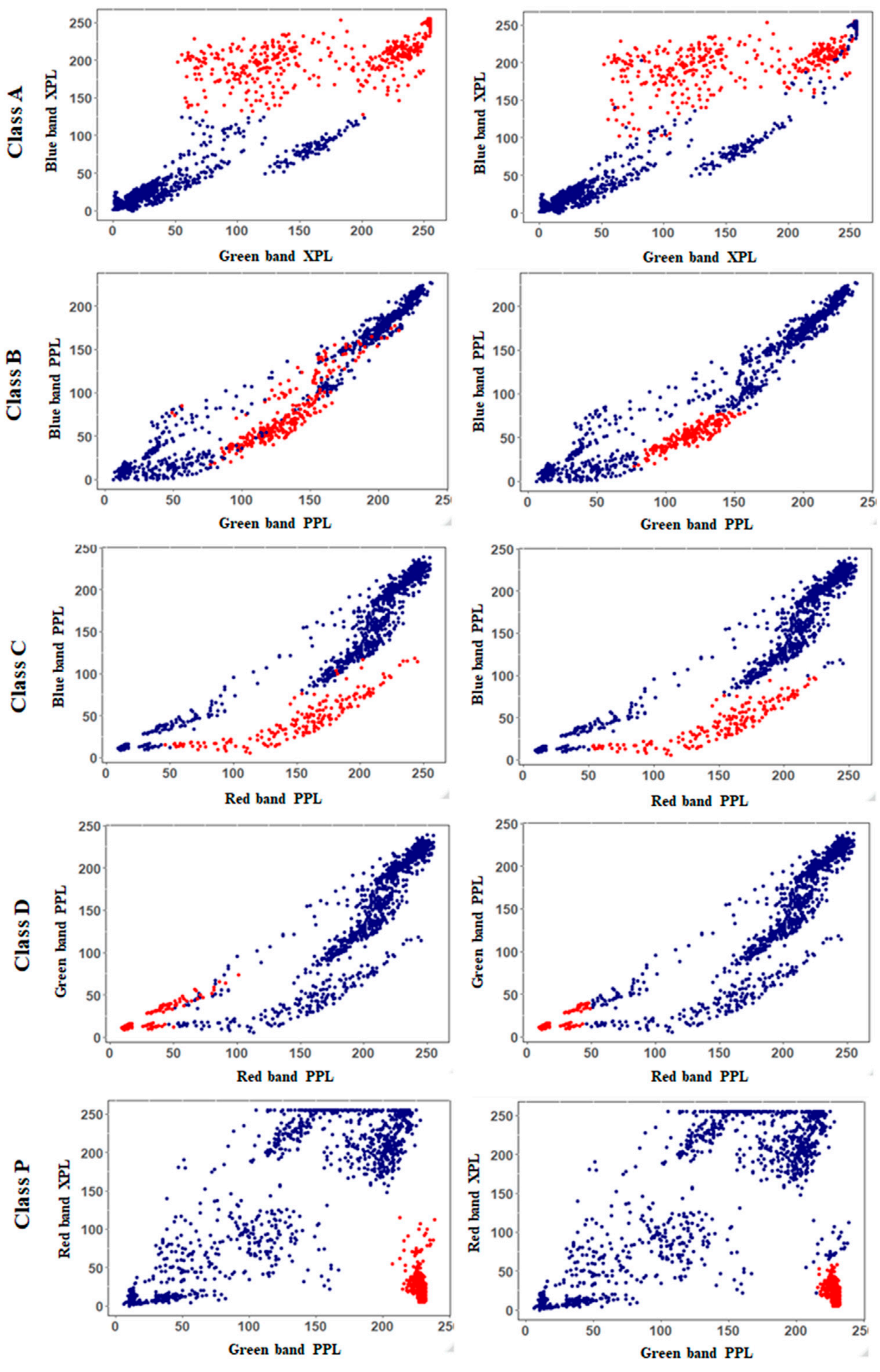

FIGURE 5 | Scatter-plots of brightness values obtained in selected bands for each class. Left-hand column shows the classes without data cleaning and right-hand column the classes after the application of data cleaning. The highest point reduction is shown in class B. Red points represents the level of decomposition of interest.

TABLE 3 | Number of sampling points used (PDE) for each class and their intervals of brightness values for each band analyzed before and after of data cleaning.

Class	Bands/Light		Without cleaning data		Cleaning data	
			Training points	Brightness values	Training points	Brightness values
A. No decomposition	G	XPL	476	52–255	476	52–255
	B			102–255		102–255
B. Light	G	PPL	301	49–215	203	77–157
	B			17–177		17–79
C. Moderate	R	PPL	88	46–210	79	46–210
	G			6–117		6–82
	B			0–92		0–32
D. Strong	R	PPL	176	9–101	153	9–73
	G			9–74		9–49
P. Porosity	G	PPL	370	207–239	343	207–239
	R	XPL		5–115		5–58

TABLE 4 | Bands and light source used to generate the models for each level of decomposition evaluated. The information that is presented is derived from the data cleaning.

Class/Degree	Light sources	Band			Discriminant function	Centroid
		R	G	B		
A. No decomposition	XPL		*	*	(G*−0.01516403) + (B*0.04774093) −3.218647	0.8040
B. Light	PPL		*	*	(G*0.05868941) + (B*−0.06535330) −0.6480741	0.769385
C. Moderate	PPL	*	*	*	(R*−0.08307243) + (G*-0.16502634) + (B*0.07993119) −0.5141844	2.6354
D. Strong	PPL	*	*		(R*−0.06047865) + (G*0.03148932) +6.758695	2.4631
P. Porosity	PPL		*		(G*0.03305831) + (R*0.02557389)	1.3942
	XPL	*			−2.04559 (G*0.02653818) + (G*0.01991728) −1.660535	

TABLE 5 | Overall, user's and producer's accuracy as well as Kappa coefficient of models applied in the classification of decomposition of organic matter. These values were obtained from the initial data and after a cleaning process.

Class/Decomposition degree	Without cleaning data			Kappa Coef.	Cleaning data			Kappa Coef.
	Accuracy (%)				Accuracy (%)			
	Producer	User	Overall		Producer	User	Overall	
A. No decomposition	97.6	87.1	94.9	0.89	99.4	98.8	99.4	0.99
B. Slightly decomposed	75.9	70.7	89.1	0.66	99.1	68.2	93.9	0.78
C. Moderately decomposed	87.3	86.4	96.1	0.85	92.5	77.7	96.6	0.82
D. Strongly decomposed	100	77.9	96.7	0.86	100	73	96.2	0.82
P. Porosity	100	98.3	99.6	0.99	100	91.6	98.1	0.94

DISCUSSION

Data Collection and Classification

The extraction of brightness values directly from the raster images provided descriptive statistics that were used to determine class membership (Foody and Mathur, 2006). This procedure allows for direct analysis of the data and establishing degrees of decomposition of organic matter with an increased reliability.

The high-resolution images obtained in this research of just over 2,000,000 pixels in an individual image and up to 586,000,000 pixels in a ×2 mosaic make traditional sampling impractical (Congalton, 1991; Foody and Mathur, 2006). For example, Congalton (1988) suggested sampling 1% of the mapped area; however, this would mean a total of 20,000 pixels per category without considering that classes do not have the same representativeness in the images.

We found that the sampling intensity can be between 160 and 537 training pixels for each class. Congalton (1991) recommends using 50 pixels as the minimum number of units to perform classifications, while Mather (2004) suggests that 30 training pixels are helpful for each class regardless of each classification method. Aydemir et al. (2004) set a minimum of 100 points for each class to obtain the brightness values of the features evaluated on thin sections of soil.

It is essential to highlight that the expert knowledge used to generate the classification reduced the sampling intensity due to the choice of representative sites as significant features of interest for the proposed classes, as established by Lu and Weng (2007). This procedure allows the proper collection of

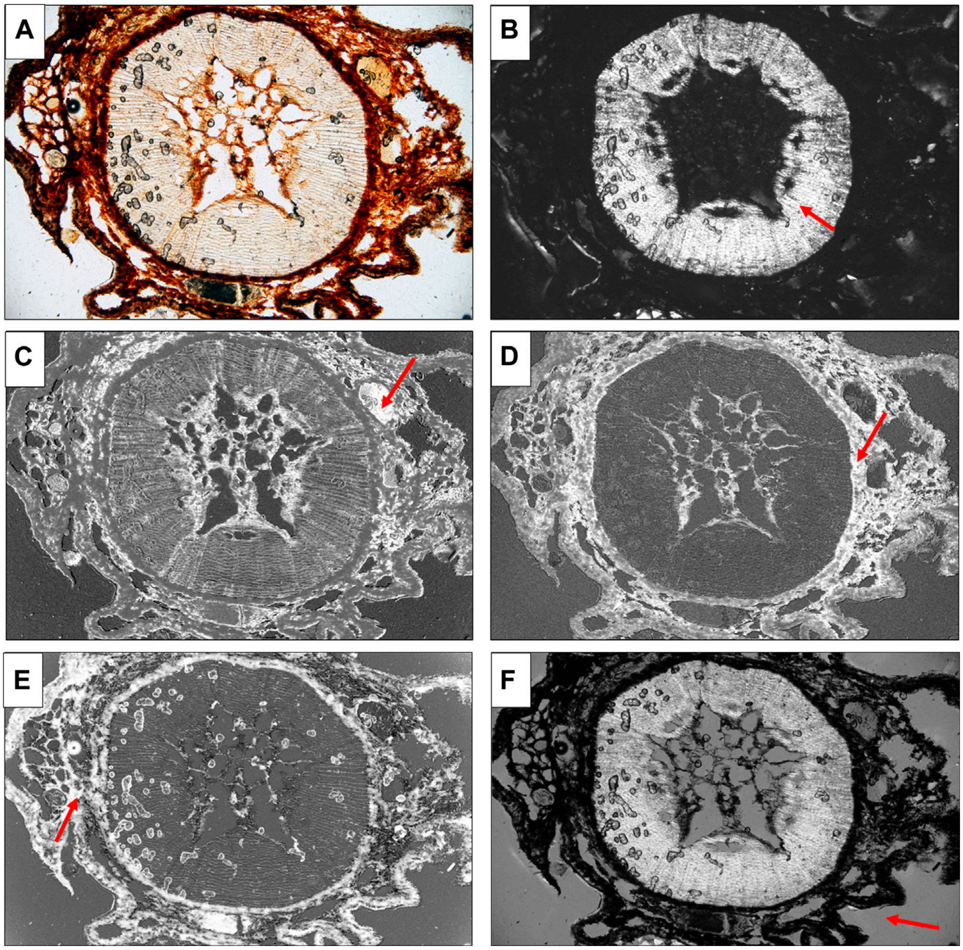

FIGURE 6 | Application of linear models to identify the decomposition levels of organic matter, which shows a lighter colour (red arrows) than the rest of the components. **(A)** Original image in PPL, **(B)** No decomposition, **(C)** Light, **(D)** Moderate, **(D)** Strong, and **(E)** Porosity. In this last case the model creates a balance between PPL and XPL and generate the porous space appears gray. Frame length 5.5 mm. Andosols-Texcoco, Mexico.

data from the proposed categories and the correct class assignment to a pixel. Blamire (1996) mentions that differences in sampling intensity (training fields) are attributable to the representativeness of the class in the image and its complexity to be classified.

Degrees of Brightness

In the first stage of this research, the analysis of different degrees of decomposition is visual and qualitative; therefore, errors in classification are introduced by confusing the different shades of colour and the degree of membership of the pixels to the predetermined classes. For this reason, re-classification of data was convenient to increase the accuracy of the models and to achieve brightness intervals that better represented the decomposition levels of organic matter.

Data cleanse or properly referred as data purge decreased the values identified as non-distinctive within each class (Arai, 1992; Mather, 2004), and resulted in a more refined representation of classes (Foody and Mathur, 2006). In addition, data purge is necessary in quantitative research so as to bring data to a quality and reliability levels to be used for statistical modelling (Van der Loo and de Jonge, 2018).

As regards to the varying degrees of organic matter decomposition, Gutiérrez-Castorena et al. (2018) reported intervals that differ from those presented in this study. This is because the authors established three categories of degrees of decomposition (light, moderate, and strong) instead of four. And the image processing performed by these authors was more complex; therefore, the brightness values were different.

Optical Characteristics of Degrees of Organic Matter Decomposition and Their Relationship to Brightness Values

The brightness values showed overlap, mainly because of the nature of the decomposition of organic matter. The decomposition is a gradual process; therefore, transitions between different stages present abrupt or diffuse boundaries according to their optical properties in the different light sources

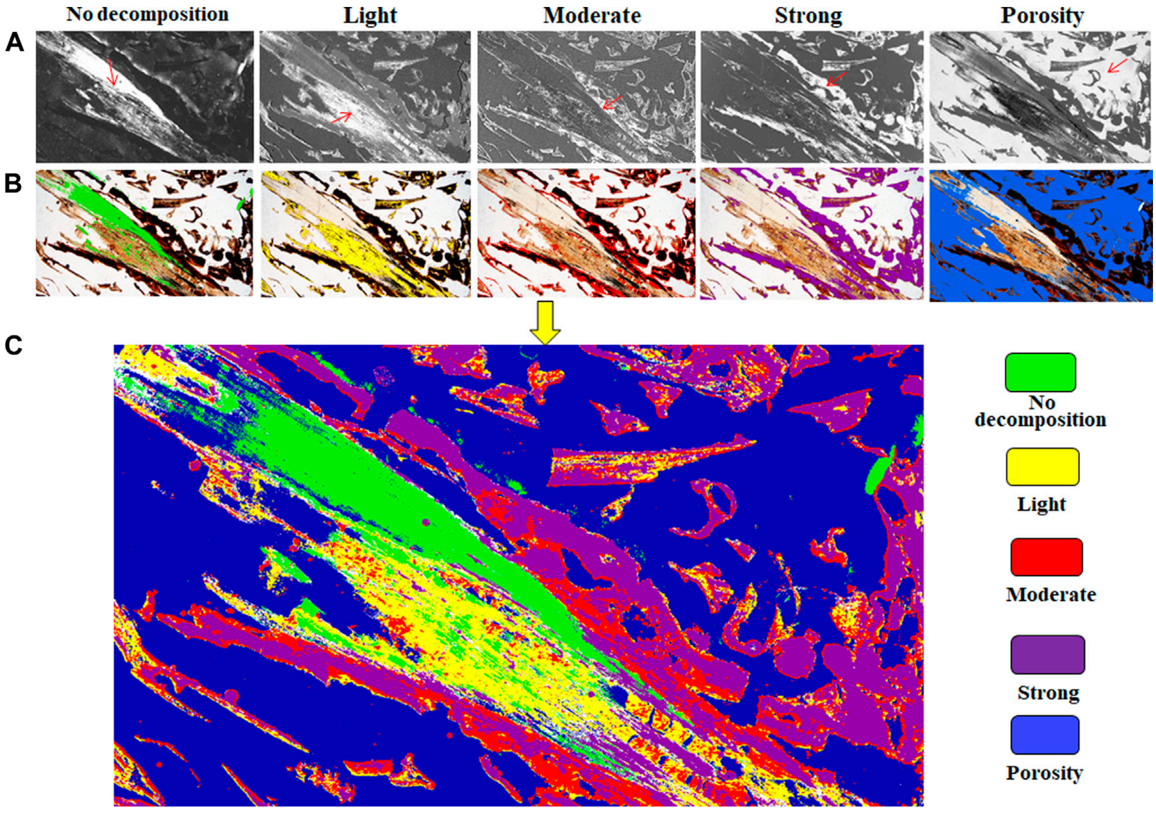

FIGURE 7 | (A) Application of models and creation of thematic maps from individual images of thin sections of composting process. **(B)** Extraction of decomposition levels and **(C)** generation of thematic maps resulting from the union of the layers generated in the previous step. Frame length 9 mm.

(Bullock et al., 1985). Nonetheless, the overlapping intervals provide a general idea of how classes can be described and characterized (Marschallinger 1997; Adderley et al., 2002).

This criterion has been used by some authors, but for other soil components. For example, Adderley et al. (2002) determined the degrees of brightness of carbonates in each band of the XPL, where the feature of interest is best represented by its high birefringence, in what is called the "pure signature" (Gutiérrez-Castorena et al., 2018). This feature occurs in brightness values close to 255 in the red, green, and blue bands in XPL. This condition can be explained by two optical properties: contrast and sharpness, which are essential for establishing relationships between the feature of interest and the adjacent materials (Bullock et al., 1985; Stoops, 2003). Carbonates have prominent contrast and abrupt sharpness in XPL, a light source where the feature is enhanced (Bullock et al., 1985).

In the case of organic matter decomposition, materials without decomposition are better characterized in XPL caused by the high cellulose birefringence (Babel, 1975; Bullock et al., 1985; Stoops, 2003), with prominent contrast, and abrupt sharpness. The behaviour is similar in the class with high decomposition, but characterized in PPL, where the contrast is also sharp, and the colors are darker than any other level of decomposition (Bullock et al., 1985). Therefore, the identification of the light source is very important for the delimitation of the component based on its optical properties.

In class B, the sharpness is diffuse, and the contrast is faded, hence this class involves a critical transition, i.e. decrease its birefringence in XPL, which indicates the decomposition of the cellulose fibres (Babel, 1975) and present yellowish/brown colorations in PPL (Bullock et al., 1985; Stoops, 2003). This class was the most difficult to characterize and showed the most significant overlap during the classification process. Finally, it was impossible to characterize an intermediate "subclass" between class A and B, although more sampling sites were placed on the unclassified pixels. In this sense, this intermediate class deserves special attention and more exhaustive analysis to complete its characterization.

Finally, the porosity required two light sources for its extraction due to the similarity with the characteristics of some state of decomposition of the organic components. For example, highly decomposed organic material (Class D) and porous space are isotropic in XPL (Bullock et al., 1985), and some light brown tones of non-decomposed or lightly decomposed organic material can be confused on light intensity. Therefore, using two bands on two light sources creates a balance and dramatically enhances the feature. Gutiérrez-Castorena et al. (2018) found that porosity, in the case of Andosols, is better characterized by PPL and XPL because of the confusion caused by andic materials that present isotropic nature.

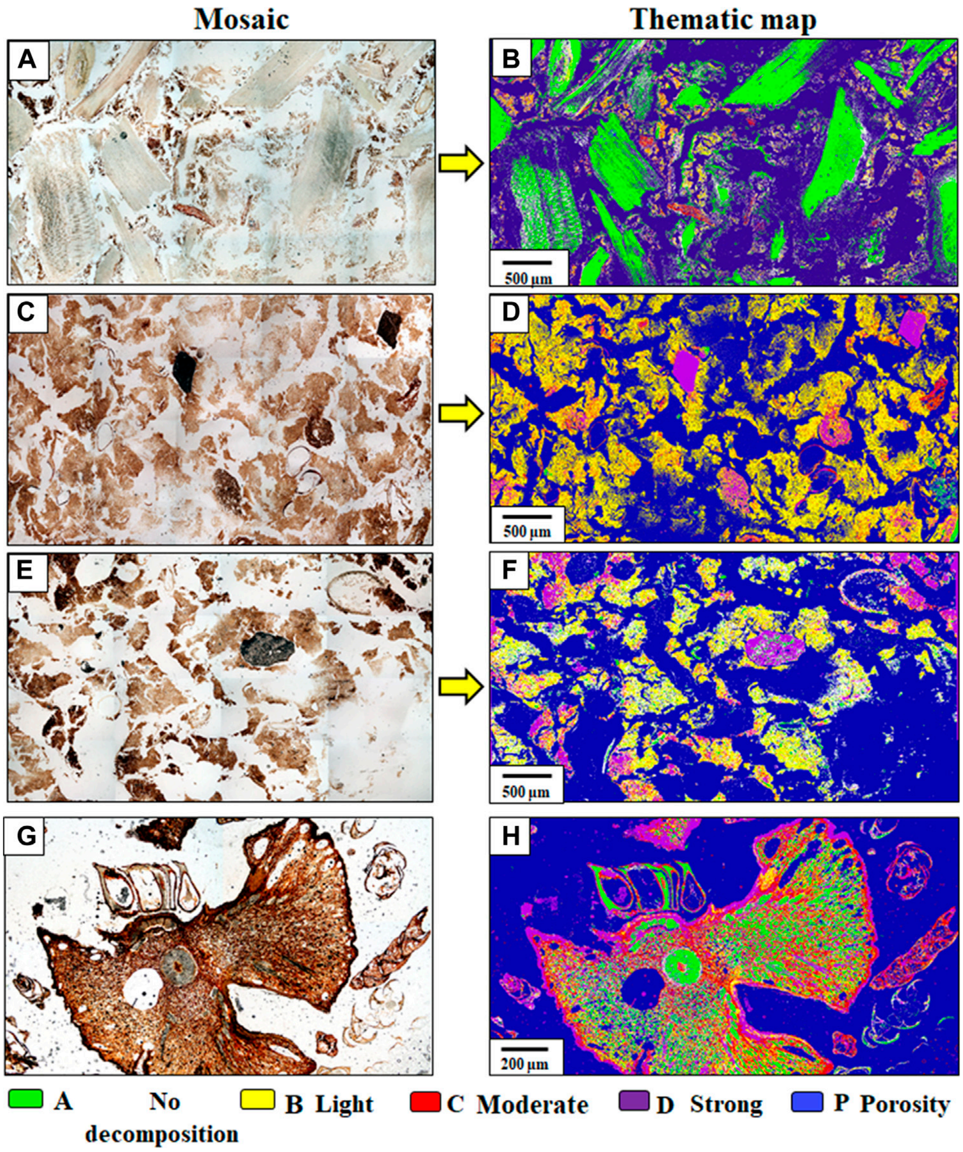

FIGURE 8 | Application of decomposition models on thin sections of composting process and creation of thematic maps from high-resolution mosaics. **(A,C,E,G)** original mosaics; and **(B,D,F,H)** classified mosaics.

TABLE 6 | Quantification of decomposition levels of organic matter in training and validation images. The superscript indicates the figure from which the quantification was performed.

Organic materials images		Class A	Class B	Class C	Class D	Class P	Total
					%		
Training	1. *Cupressus*[6A] (Forest)	8.4	14.4	6.7	20.1	54.8	104.4
	2. Humus (Forest)	11.8	12.4	6	21.4	51.4	103
	3. Compost (Manure)	22.7	8.7	3	17.4	56.4	108.2
	4. Organic amendments	17.1	4	1.9	23.8	50.4	98.2
Validation	5. Compost[7B]	16.9	15	1	5.9	59	79.9
	6. Compost[7D]	22.7	17.5	1	6.4	38.7	86.6
	7. Compost[7F]	7	9.1	11.3	10.2	59	96.6
	8. Compost[7H]	30.7	9.2	1.7	6.1	38.2	85.9
	9. Mosaic[8B]	26.6	3	1.5	0.7	63.9	95.7
	10. Mosaic[8D]	4.3	44.5	5.1	5	52.3	111
	11. Mosaic[8F]	3.1	13.1	2.5	5.4	64.5	85

Linear Discriminant Analysis

The importance of creating models or discriminating functions of organic matter decomposition levels is that they can represent the process through mathematical relationships or equations (Motta and Pappalardo, 2012). Furthermore, when these models are applied to other new cases (images), automation of classification and quantification of decomposition levels becomes easier to carry out. An additional advantage of using the models is that the user does not necessarily have to be an expert in soil micromorphology since the discriminant functions have been previously created based on expert knowledge.

Some statistical methods have been used previously to analyze images of other soil components in thin sections. These routines include supervised and unsupervised classification (Tarquini and Favalli, 2010; Sauzet et al., 2017; Gutiérrez-Castorena et al., 2018), ANOVA (Brzychcy et al., 2012), and multivariate analysis such as that of principal components (Terribile et al., 1995; Jangorzo et al., 2014). Gutiérrez-Castorena et al. (2018) used the supervised and unsupervised classification in organic materials; however, the processing was complex and demanding in computational terms because map operators were carried out with the composite images, i.e., in their original color composition (RGB). Sugiyama, 2007 mention that separate bands allowed less information processing and computational time when performing image analysis.

Accuracy

Overall precision values obtained were very high (greater than 94%) for all cases because of the LDA's robustness (Foody and Mathur, 2006). Additionally, the percentages obtained are comparable with other supervised grading methods previously used for thematic mapping in soil thin sections (Sauzet et al., 2017; Gutiérrez-Castorena et al., 2018).

In addition, producer's accuracy increases significantly, both before and after applying data purge, which means that the omission error decreases; that is, a smaller number of pixels were not omitted from the class category. This statistic indicates how well a specific area can be mapped (Story and Congalton, 1986); however, when user's accuracy is evaluated, the values are lower, especially when data cleanse is applied. This indicates that it increases the commission error, i.e., the probability that a pixel falls into one category and belongs to another.

According to Jensen (2015), kappa coefficient >0.80 represents a high agreement between the classification map and the reference information. Values between 0.4 and 0.8 represent a moderate agreement and <0.40 a poor/poor agreement. As a result, classes A, C, D and P show a high concordance and class B a moderate one. Even this is the same classification before applying data clean-up. According to previous statisticians, the discriminant functions generated in this research can classify the levels of organic matter decomposition into O horizons.

An important aspect to mention is that it is necessary to check the execution of the model visually. Consequently, validation through acquired knowledge or what is known as "expertise" is very important in micromorphological analysis and should even be considered as an additional criterion to numerical data (Mather, 1987). Hence, after the generation of a model and checking the accuracy, it was visually analyzed whether the classification was correct; in other words, it is a method that employs an expert system.

Application of the Model and Quantification

With the application of the model, new pixel values are generated, the images are improved, and the feature of interest is highlighted, while the rest of the components are opaque. The application of the model is fast because a "macro-model" can be built within the software, as a basis for adding bands of the new image. Therefore, there is no need to rewrite the entire process every time the image analysis for such a purpose is performed. Also, it is necessary to consider that this process is straightforward when there is a high quality of elaboration within the thin section (birefringence in porous space in XPL). An additional issue is when a pixel falls into two classes because the model can overestimate or underestimate the class area. The second case is attributed to the fact that a pixel with a not well defined membership may be more susceptible to fall into two classes when using a binary classification algorithm. An option to improve the separability between classes is the application of map algebra. In this routine, the layer with the highest representativeness serves as the basis for subtraction over the one that overlaps the class of interest. Protz and VandenBygaart (1998) applied this same technique in clayey coatings, which was obtained by subtracting pores and minerals.

Despite the difficulties mentioned above, discriminant functions can be applied to research aimed at assessing decomposition levels in the O horizon, in the O-A transition, or to composting materials, as a way to probe/explore the decomposition status of organic matter. The recommended routine is: photographing, decomposition of strips, application of models, and quantification. The user will also decide whether, apart from applying the models, other processes (such as map algebra) need to be carried out to eliminate class overlap, as described above.

CONCLUSION

The banding of the images obtained from different light sources of the petrographic microscope proved to be very useful for analyzing the brightness values associated with each level of decomposition of organic matter. Each level was related to one or two light sources (only PPL and XPL) and the combination of two or three bands.

The functions were generated using linear discriminant analysis to classify the degrees of organic matter decomposition with high precision. Furthermore, the application of the functions automated the creation of layers of the organic matter decomposition degrees of to create thematic maps.

Finally, this research represents a first approach to creating classification models in soil thin sections and may be helpful in the generation of more classification models for other soil components using different statistical methods.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

TG-V and MG-C writing and review of document, data collection, performing statistical analysis.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Changes in Soil Phosphorus Pools in Long-Term Wheat-Based Rotations in Saskatchewan, Canada With and Without Phosphorus Fertilization

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Phosphorus (P) is an essential nutrient for all organisms, and many crops require P fertilization for optimum yield. However, there are concerns about the P in agriculture, including the sustainability of phosphate sources for fertilizers and water quality problems from P loss in runoff from agricultural lands. Most crops do not use all of the P added each year as fertilizer, leaving residual soil P that could potentially be used by subsequent crops, minimizing the need for additional fertilization. However, more information is needed to understand soil residual P pools, and their availability to crops. In Swift Current, SK, Canada, a long-term study was initiated in 1967, with four wheat-based rotations [including continuous wheat (CW), fallow-wheat-wheat (FWW), fallow-wheat (FW) and lentil-wheat (WL), with P fertilization and with or without nitrogen (N) fertilization. In 1995, P fertilization ceased on subplots in the CW and FWW rotations, and in 2008 for the FW and WL rotations. This study examined changes in soil P pools (total P, organic P, and Olsen P) from 1995 to 2015 for CW and FWW rotations and from 2008 to 2016 for FW and WL rotations, plus crop yield and grain and straw N and P concentrations. Long-term P addition increased concentrations of soil total and Olsen P in FWW, CW and FW rotations, particularly in plots without N fertilization. However, calculated P depletions based on fertilizer addition and crop P removal were negative only for plots without N fertilization. Cessation of P fertilization reduced concentrations of soil total and Olsen P, especially in plots with N fertilization. Annual yields were affected more by N fertilization and precipitation than P fertilization. Grain and straw P concentrations were not significantly reduced with short-term P cessation in FW and WL rotations, but were reduced with longer-term P fertilizer cessation in FWW and CW rotations.

Keywords: fertilizer cessation, legacy phosphorus, drawdown, organic phosphorus, total phosphorus, Olsen phosphorus, phosphorus use efficiency

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INTRODUCTION

Phosphorus (P) is an essential element for all organisms, including crops. In order to maximize crop yields, chemical and/or organic (e.g., manure) fertilizers have been added to soils for decades or more to increase soil P concentrations (Way, 1850; Rubæk et al., 2013; Withers et al., 2019). Intensification of agriculture in the mid-to late-20th century substantially increased P fertilizer use, often far beyond what was required to replace P removed in crops and resulting in high P concentrations in many agricultural soils (MacDonald et al., 2011; Bruulsema et al., 2019; Withers et al., 2019). These high soil P concentrations are often maintained by producers to minimize productivity risks related to soil P fertility (Withers et al., 2019). However, application of fertilizer P beyond the agronomic optimum can result in P loss from land to water, by erosion of particulates or through dissolved P in runoff or drainage waters (Ulén and Jakobsson, 2005; Cade-Menun et al., 2013; Schoumans et al., 2014; Cade-Menun et al., 2017; Liu et al., 2019). This P loss is a major contributor to eutrophication and water quality problems (Sharpley et al., 1994) and efforts are underway in many countries to manage the P that has accumulated in soils (Withers et al., 2019). It is also widely recognized that the rock phosphate used to produce chemical P fertilizers is a finite resource requiring careful management for long-term sustainability (Djodjic et al., 2005; Rubæk et al., 2013; Withers et al., 2019).

Application of P fertilizers is often based on soil tests, which need to be specifically calibrated to crops and soils. And it is widely recognized that not all fertilizer P added each year is used by that year's crops, even when applied conservatively based on soil test recommendations (Sattari et al., 2012). Instead, P in excess of crop requirements is retained in soil by sorption and/or precipitation reactions, increasing concentrations of soil test P and total P in soils over time (Selles et al., 2011; Rubæk et al., 2013; Rowe et al., 2016; Cade-Menun et al., 2017). This residual, or legacy, P is defined as the difference between inputs (from fertilizer products, deposition and weathering) and outputs (removal in harvested crops or through P loss in runoff or erosion; Sattari et al., 2012), and needs to be carefully managed to reduce the environmental risk. This includes management practices to reduce P transport (e.g. erosion controls), but also requires management to reduce soil test P concentrations when they exceed agronomic optima (Withers et al., 2019). There is also growing recognition that legacy P could be more available to crops than originally thought, reducing or even replacing fertilizer P applications and thereby conserving finite rock phosphate sources (Sattari et al., 2012; Rubæk et al., 2013; Rowe et al., 2016; Withers et al., 2019).

Fertilizer cessation is a key practice to draw down legacy P concentrations to agronomically-optimal levels to reduce the potential for P loss. However, guidelines are needed to manage fertilizer cessation, in order to reduce soil test P concentrations without any negative impacts on yield (Withers et al., 2019). This requires data from fertilizer cessation studies from different crops grown in a wide range of conditions, including: the time required to draw down soil test P concentrations; changes in soil P pools beyond soil test P, such as total P and organic P; and the effects of different management practices on the rate of P drawdown. Long-term studies are an essential source for this information, particularly with respect to the time frame needed to reduce soil P concentrations, which will vary with factors including soil type and texture, initial soil P concentrations, and other influences on crop health (Rubæk et al., 2013; Cade-Menun et al., 2017; Liu et al., 2019; Appelhans et al., 2020).

In Swift Current, SK, Canada, a long-term study of wheat-based crop rotations with P fertilization, and with and without N fertilization, was established in 1967; subplots without P fertilization were established in 1995 for rotations with wheat every year (continuous wheat; CW) and with fallow every third year (fallow-wheat-wheat, FWW; Selles et al., 1995; Selles et al., 2011). In 2005, soil test P concentrations had decreased in P cessation plots for CW and FWW rotations with N fertilization compared to plots with continued P fertilizer application (Selles et al., 2011). Grain production was reduced by 10% for the CW wheat with P fertilizer cessation, but there was no effect on yield for the FWW rotation, suggesting that legacy P was retained in soils in plant-available forms for many years after fertilizer application (Selles et al., 2011). However, only changes in soil test (Olsen) P concentrations were determined, without examining changes in other soil P pools.

The objective of this study is to continue the work published in Selles et al. (2011), to understand the long-term effects of continued P fertilization versus P fertilizer cessation on wheat-based crop rotations in the Northern Great Plains of North America. Fertilizer cessation plots were established for two additional crop rotations in 2008: alternating fallow and wheat (FW) rotations, and lentil-wheat (WL) rotations. Soil test (Olsen) P was monitored for an additional decade (2006–2015) in the same CW and FWW rotations used by Selles et al. (2011) and in the new plots (2008–2016). In addition to Olsen P, soil total P (TP) and organic P (Org P) were determined each year from 1995 to 2015 for CW and FWW rotations, and from 2008 to 2016 for WL and FW rotations. It was hypothesized that a) concentrations of Olsen P, TP and Org P would increase with continued P fertilization for all crop rotations and decrease when P fertilization stopped; b) Olsen P concentrations would change more with continued fertilization or fertilizer cessation than TP and Org P concentrations; c) decreases in Org P after fertilization cessation would indicate mineralization of Org P to meet crop P demands; and d) crop yields and grain P concentrations would decrease with P fertilizer cessation.

MATERIALS AND METHODS

Field Sites and Management

Samples were collected from an experiment established in 1967 on Orthic Brown Chernozem (Canadian classification; Aridic Haploboroll, USDA; Haplic Kastanozem, FAO) soils at the Agriculture and Agri-Food Canada Swift Current Research and Development Centre in Saskatchewan, Canada (latitude 50°170′N, longitude 107°480′W). More details are available in Selles et al. (1995, 2011), Liu et al. (2015), and Chen et al. (2021). This study used plots for four crop rotations: CW, FWW, FW and WL. The CW, FW and FWW rotations were established in 1967; the WL plots were established in 1982. All phases for each rotation were present each year, with three replicate plots per treatment. From establishment, plots were fertilized with 10 kg P ha^{-1} yr^{-1} (monoammonium phosphate, MAP) and either a) no N fertilizer (the -N+P treatment); or b) 32–50 kg N ha^{-1} yr^{-1} (ammonium nitrate, NH_4NO_3 from 1967 to 2007, urea from 2008; the +N+P treatment), with N application rates based on soil testing each spring. No fertilizer was applied during the fallow phase of FW and FWW rotations, and no N fertilizer was applied

TABLE 1 | Phosphorus (P) concentrations in various pools (TP, total P; Org P, organic P; Olsen P, bicarbonate-extractable P) for the fallow-wheat-wheat (FWW) rotation, analyzed by fertilizer treatment, for 1995–2015. Values are means (std. err); n = 150; different letters among treatments for each P pool indicate significantly different means (α = 0.05).

			Fertilizer treatment					
P Pool	**Units**	**Depth (cm)**	**+N+P**	**+N-P**	**-N+P**	**-N-P**	**N only**	**None**
TP	mg kg^{-1}	0–7.5	573.3 a (4.51)	536.9 b (3.36)	581.8 a (4.97)	542.5 b (4.09)	511.7 c (4.12)	497.2 c (3.61)
TP	mg kg^{-1}	7.5–15	493.5 a (5.28)	473.9 a (4.82)	477.4 ab (5.57)	471.9 b (4.81)	464.9 b (4.56)	461.5 b (4.03)
TP	kg ha^{-1}	0–15	949.0 a (8.28)	900.9 b (7.03)	956.7 a (8.35)	919.0 bc (6.69)	881.6 cd (7.37)	866.8 d (6.47)
TP Δ[a]	kg ha^{-1}	0–15	24.4 ab (24.6)	−12.7 ab (25.8)	57.1 a (29.4)	12.3 ab (19.6)	−56.4 b (26.1)	−11.5 ab (13.9)
Org P	mg kg^{-1}	0–7.5	292.7 (4.66)	293.0 (4.27)	292.3 (4.54)	294.3 (4.20)	281.7 (4.31)	284.3 (4.00)
Org P	mg kg^{-1}	7.5–15	282.9 (5.08)	286.3 (5.29)	278.1 (4.90)	277.9 (4.50)	271.6 (4.39)	279.1 (4.30)
Org P	kg ha^{-1}	0–15	516.0 (7.82)	519.7 (7.43)	519.0 (6.56)	519.9 (5.83)	501.2 (6.98)	511.3 (7.03)
Org P Δ[a]	kg ha^{-1}	0–15	70.8 (26.6)	14.7 (28.2)	36.0 (20.1)	6.97 (17.4)	26.8 (26.2)	13.0 (18.9)
Org P	% TP	0–7.5	51.2 bc (0.77)	54.7 a (0.75)	50.7 c (0.84)	54.3 ab (0.71)	55.4 a (0.87)	57.6 a (0.86)
Org P	% TP	7.5–15	57.6 (0.94)	60.5 (0.96)	58.7 (0.94)	59.4 (0.96)	59.0 (0.98)	60.7 (0.87)
Olsen P	kg ha^{-1}	0–15	27.6 b (1.05)	16.5 d (0.58)	34.7 a (1.05)	23.0 c (0.65)	9.93 e (0.37)	9.80 e (0.45)
Olsen P Δ[a]	kg ha^{-1}	0–15	15.6 a (3.71)	−2.53 b (1.80)	17.1 a (3.69)	2.95 b (2.06)	0.23 b (1.10)	0.95 b (1.80)
P Depletion[b], mean kg ha^{-1}			1.94 c (0.39)	10.2 a (0.32)	−0.08 c (0.37)	8.28 b (0.35)	7.70 b (0.36)	7.44 b (0.24)
P Depletion[b], cumul. kg ha^{-1}			27.2 c (6.69)	142.1 a (4.39)	−1.13 d (−4.51)	115.9 b (3.28)	107.8 b (3.46)	104.2 b (2.90)

[a]*Net change, 1995–2015.*
[b]*P depletion, grain P minus fertilizer P.*

TABLE 2 | Phosphorus (P) concentrations in various pools (TP, total P; Org P, organic P; Olsen P, bicarbonate-extractable P) for the continuous wheat (CW) rotation, analyzed by fertilizer treatment, for 1995–2015. Values are means (std. err); n = 63; different letters among treatments for each P pool indicate significantly different means (α = 0.05).

			Fertilizer treatment			
Phosphorus pool	**Units**	**Depth (cm)**	**+N+P**	**+N-P**	**-N+P**	**-N-P**
TP	mg kg^{-1}	0–7.5	592.7 ab (7.36)	552.1 c (6.32)	617.8 a (8.89)	573.9 bc (6.88)
TP	mg kg^{-1}	7.5–15	475.0 b (8.40)	472.7 b (6.42)	509.5 a (9.14)	495.3 a (8.92)
TP	kg ha^{-1}	0–15	892.9 c (12.2)	861.3 c (9.15)	1,002.3 a (14.2)	954.0 b (12.8)
TP Δ[a]	kg ha^{-1}	0–15	66.6 ab (50.0)	9.90 ab (51.8)	159.6 a (36.9)	−43.2 b (45.0)
Org P	mg kg^{-1}	0–7.5	315.1 (6.11)	326.3 (7.02)	287.1 (6.40)	286.6 (7.73)
Org P	mg kg^{-1}	7.5–15	273.1 (5.25)	296.3 (7.13)	283.9 (6.41)	261.2 (5.92)
Org P	kg ha^{-1}	0–15	495.4 (8.08)	526.3 (10.8)	513.0 (8.90)	489.8 (10.1)
Org P Δ[a]	kg ha^{-1}	0–15	37.4 (24.2)	12.1 (38.7)	2.83 ab (33.6)	8.50 (27.7)
Org P	% TP	0–7.5	53.7 (1.23)	59.4 (1.39)	47.0 (1.28)	50.3 (1.42)
Org P	% TP	7.5–15	58.1 (1.16)	62.9 (1.39)	56.6 (1.45)	54.0 (1.64)
Olsen P	mg kg^{-1}	7.5–15	6.63 b (0.78)	4.46 bc (0.33)	11.8 a (1.13)	3.99 c (0.32)
Olsen P	% TP	7.5–15	1.34 b (0.14)	0.96 bc (0.08)	2.26 a (0.20)	0.81 c (0.06)
Olsen P Δ[a]	kg ha^{-1}	0–15	15.4 b (2.17)	−8.13 c (2.19)	30.3 a (5.18)	−2.05 c (2.87)
P Depletion[b], mean kg ha^{-1}			1.71 b (0.39)	8.12 a (0.43)	−1.70 c (0.35)	6.93 a (0.36)
P Depletion[b], cumul. kg ha^{-1}			35.9 b (1.73)	170.6 a (1.73)	−35.6 c (1.73)	145.6 a (1.73)

[a]*Net change, 1995–2015.*
[b]*P depletion, grain P minus fertilizer P.*

to the lentil phase of the WL plots (P fertilizer was applied to both the wheat and lentil phases). In addition, the FWW rotation had a treatment receiving no P fertilization from establishment (the "N only" treatment). In 1995 for the CW and FWW rotations and in 2008 for the FW and WL rotations, sub-plots without P fertilization were established on all plots receiving P fertilizer, hereby designated as the +N-P and -N-P treatments. In the sub-plots of the N only treatment, N application stopped, resulting in no fertilization of any kind (the "None" treatment).

For most years, crops were seeded in May and harvested in August. Weed management was by mechanical tillage and herbicides, using locally recommended rates and methods. Summer fallow plots for the FW and FWW rotations were managed with additional tillage and herbicide applications. Fertilizer N was broadcast before seeding, while fertilizer P was seed-placed.

Sample Collection and Processing

Small areas (2.32 m^2) in each plot were harvested manually to determine yield and to analyze for grain and straw N and P, with plant heights and number of plants also recorded. The remaining grain was harvested with a conventional combine; straw was chopped and spread on the plots. After drying at 70°C, weights

TABLE 3 | Soil phosphorus (P) concentrations in various pools (TP, total P; Org P, organic P; Olsen P, bicarbonate-extractable P) for the fallow-wheat (FW) rotation, analyzed by fertilizer treatment, for 2008–2016. Values are means (std. err); $n = 48$; different letters among treatments for each P pool for each depth indicate significantly different means (Tukey HSD; $\alpha = 0.05$).

Phosphorus pool	Units	Depth (cm)	Treatment	
			+N+P	+N-P
TP	mg kg^{-1}	0–7.5	584.3 a (6.83)	564.4 b (546)
TP	mg kg^{-1}	7.5–15	509.6 (8.64)	494.5 (8.08)
TP	kg ha^{-1}	0–15	996.6 a (10.8)	965.2 b (8.89)
TP Δ[a]	kg ha^{-1}	0–15	21.2 (28.9)	3.84 (23.7)
Org P	mg kg^{-1}	7.5–15	280.6 (8.76)	280.7 (9.10)
Org P Δ[a]	kg ha^{-1}	0–15	–30.3 (31.3)	1.40 (28.4)
Olsen P	mg kg^{-1}	0–7.5	31.0 a (1.00)	26.0 b (0.70)
Olsen P	mg kg^{-1}	7.5–15	14.6 (1.04)	12.3 (0.97)
Olsen P	kg ha^{-1}	0–15	40.4 a (1.63)	34.0 b (1.17)
Olsen P Δ[a]	kg ha^{-1}	0–15	19.5 (3.41)	12.6 (2.18)
Olsen P	% TP	0–7.5	5.30 a (016)	4.62 b (0.13)
Olsen P	% TP	7.5–15	2.81 (0.18)	2.44 (0.17)
P Depletion[b], mean kg ha^{-1}			3.25 b (0.70)	11.7 a (0.76)
P Depletion[b], cumul. kg ha^{-1}			13.0 b (1.80)	46.8 a (2.63)

[a] *Net change, 2008.*
[b] *P depletion, grain P minus fertilizer.*

TABLE 4 | Soil phosphorus (P) concentrations in various pools (TP, total P; Org P, organic P; Olsen P, bicarbonate-extractable P) for the wheat-lentil (WL) rotation, analyzed by fertilizer treatment, for 2008–2016. Values are means (std. err); $n = 48$.

Phosphorus pool	Units	Depth (cm)	Treatment	
			+N+P	+N-P
TP	mg kg^{-1}	0–7.5	659.1 a (9.17)	616.6 b (8.98)
TP	mg kg^{-1}	7.5–15	531.4 (8.80)	510.4 (9.85)
TP	kg ha^{-1}	0–15	1,041.7 a (12.9)	987.4 b (14.8)
TP Δ[a]	kg ha^{-1}	0–15	–25.4 (38.1)	–59.2 (34.2)
Org P	mg kg^{-1}	0–7.5	328.9 (8.96)	329.5 (7.78)
Org P	mg kg^{-1}	7.5–15	307.1 (7.38)	306.6 (7.32)
Org P	kg ha^{-1}	0–15	560.9 (12.5)	560.9 (11.1)
Org P Δ[a]	kg ha^{-1}	0–15	–31.4 (16.2)	–30.1 (31.0)
Org P	% TP	0–7.5	50.5 (1.85)	53.9 (1.54)
Org P	% TP	7.5–15	58.1 (1.40)	60.7 (1.58)
Olsen P	mg kg^{-1}	0–7.5	37.9 a (1.66)	26.3 b (1.09)
Olsen P	mg kg^{-1}	7.5–15	10.0 (0.88)	8.12 (0.62)
Olsen P	kg ha^{-1}	0–15	39.4 a (1.87)	28.5 b (1.19)
Olsen P Δ[a]	kg ha^{-1}	0–15	16.2 a (4.20)	3.70 b (2.86)
Olsen P	% TP	0–7.5	5.77 a (0.25)	4.30 b (0.17)
Olsen P	% TP	7.5–15	1.87 (0.15)	1.58 (0.11)
Wheat P Depletion[b], mean, kg ha^{-1}			7.14 b (1.31)	13.9 a (1.11)
Lentil P Depletion[b], mean, kg ha^{-1}			–0.60 b (0.97)	9.09 a (0.95)
P Depletion[b], cumul. kg ha^{-1}			26.2 b (3.94)	92.1 a (1.92)

[a] *Net change, 2008–2016.*
[b] *P depletion, grain P minus fertilizer.*

were recorded and then grain and straw samples were ground. See Selles et al. (2011) for more details.

Post-harvest annually (October-November), three soil cores (10-cm diameter) per plot per treatment were collected, which were divided into surface (0–7.5 cm) and subsurface (7.5–15 cm) depths and composited into a single sample per depth per treatment plot. Samples were air-dried, sieved (<2 mm) and stored in paper envelopes at room temperature until chemical analyses. Prior to 2008, soil samples were not collected from fallow plots; from 2008 onward, all plots were sampled each year. Soil samples were archived for CW and FWW plots from 1995 and from FW and WL from 2008.

Laboratory Analysis

Soil P Pools

Bicarbonate-extractable (Olsen) P was extracted and analyzed colorimetrically in each collection year (Olsen et al., 1954; Hamm et al., 1970). Analysis for other P pools described below was done in 2008/2009 on archived samples from 1995 to 2007, and in the year following sample collection from 2008 onward. Total P (TP) was determined by digestion (Parkinson and Allen, 1975) and total organic P (Org P) was determined by the ignition method (Saunders and Williams, 1955), both with colorimetric analysis (Murphy and Riley, 1962). Bulk density data were collected for the main plots in 2021 and were used to convert chemical data from concentrations (mg kg^{-1}) to stocks of each P pool (kg ha^{-1}) for the 0–15 cm depths. There were no significant differences in bulk density for treatments within a single rotation, but bulk densities varied among rotations, especially for the 0–7.5 cm depth (**Supplementary Table S1**). As such, the bulk densities determined for each plot were used for calculations for that plot, rather than a single bulk density value for all treatments, as was used by Selles et al. (2011); however, the same bulk density was used for each plot for all years. Bulk densities were not measured in the sub-plots, and were assumed to be the same as the main plots for each treatment.

Plant Analysis and Yield Data Collection

Grain and straw samples were ground and analyzed for total P and total N by Kjeldahl digestion and colorimetric analysis (Murphy and Riley 1962; Starr and Smith, 1978).

Calculations

Data from the FWW and CW rotations from 1995 to 2015 were grouped in 3-yr blocks for a cumulative year (e.g., 1995, 1996 and 1997 were grouped into the cumulative year "1997," to include all phases of the FWW rotation for each plot. Data from the FW and WL rotations from 2008 to 2016 were similarly grouped into 2-yr blocks. Net changes in total P, organic P and Olsen P (0–15 cm, kg ha^{-1}) were determined by subtracting soil concentrations for each plot per treatment per year for the first cumulative year for each rotation (1997 for FWW and CW; 2010 for FW and WL) from the last cumulative year for each rotation (2015 for FWW and CW; 2016 for FW and WL). For each plot P, depletion was determined by subtracting the P added as fertilizer (kg ha^{-1}) from grain P concentration (kg ha^{-1}); cumulative P depletion was determined by adding annual P depletion for each plot. Straw P concentration was not included in calculations of P depletion because straw was left on each plot post-harvest.

TABLE 5 | Soil organic phosphorus (P) concentrations for the fallow-wheat (FW) rotation for which there was a significant treatment*date interaction by ANOVA, analyzed by fertilizer treatment, for 2008–2016. Values are means (std. err.); *n* = 12; different letters among treatments for each P pool for each depth indicate significantly different means (Tukey HSD; α = 0.05).

			Year			
Phosphorus pool	**Depth (cm)**	**Treatment**	**2010**	**2012**	**2014**	**2016**
Organic P (mg kg^{-1})	0–7.5	+N+P	289.5 ab (15.3)	269.8 ab (13.6)	306.8 ab (18.6)	277.8 ab (8.22)
		+N-P	323.4 a (19.6)	300.2 ab (10.5)	272.9 ab (12.5)	260.9 b (10.3)
Organic P (kg ha^{-1})	0–15	+N+P	511.4 abc (23.0)	515.4 abc (23.3)	548.5 ab (22.3)	493.6 bc (15.4)
		+N-P	522.5 abc (26.8)	569.5 a (22.7)	480.5 c (19.2)	511.4 abc (15.5)
Organic P (% Total P)	0–7.5	+N+P	47.6 cd (2.39)	47.2 cd (2.10)	53.6 abc (3.03)	47.8 bcd (1.87)
		+N-P	55.7 a (3.52)	54.3 ab (1.38)	48.9 bcd (2.38)	46.3 d (1.66)
Organic P (% Total P)	7.5–15	+N+P	56.4 xy (3.58)	56.5 xy (2.58)	56.0 xy (2.10)	50.8 y (2.07)
		+N-P	53.0 xy (2.99)	64.4 x (3.43)	51.7 y (2.21)	57.4 xy (1.89)

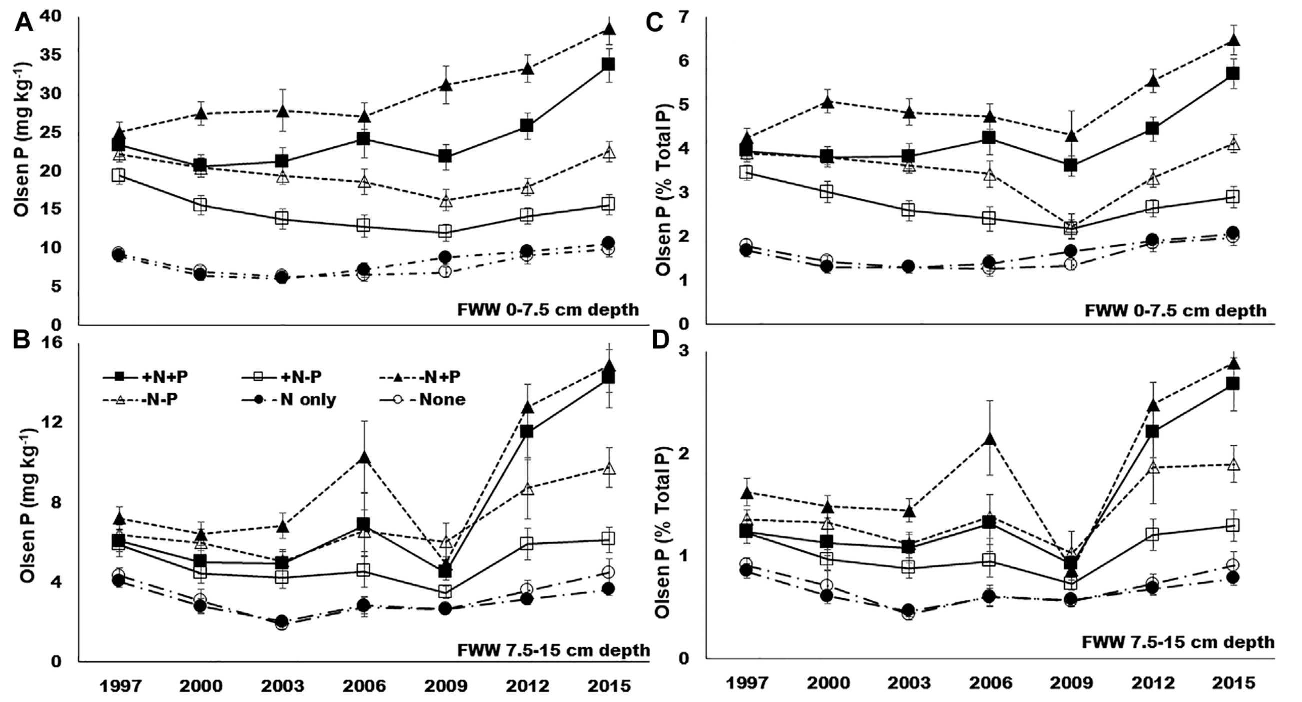

FIGURE 1 | Olsen P concentrations with a significant year*treatment interaction with ANOVA, for the fallow-wheat-wheat (FWW) rotation. Values are means ± standard error. Olsen P concentration (mg kg^{-1}), **(A)** 0–7.5 cm depth and **(B)** 7.5–15 cm depth; and Olsen P concentration as a percentage of total P concentration, **(C)** 0–7.5 cm depth and **(D)** 7.5–15 cm depth. Statistically significant differences among means (Tukey HSD; α = 0.05) are shown in **Supplementary Table S6**.

Statistical Analyses

Data were tested for normality with the Shapiro-Wilks test and transformed as needed, using log(n + 0.5); means reported in figures and tables are from untransformed data. Two-factor analysis of variance (ANOVA) was conducted (treatment, date and the treatment*date interaction) with a standard least squares model, followed by Tukey's highest significant differences (HSD) tests. Statistical analyses were performed using JMP (SAS Institute, v. 5.1), with α = 0.05. The two soil depths were not compared to each other, and were analyzed separately by the same statistical methods. Rotations were also not compared statistically to one another.

RESULTS

Soil Total P

For all rotations and depths, there were no significant interactions of treatment*year for TP (mg kg^{-1}, 0–7.5 cm and 7.5–15 cm; kg ha^{-1}, 0–15 cm), but treatment was significant for most depths and rotations and year was also significant in many cases (**Supplementary Table S2**). For all rotations, mean TP concentrations ranged from 497.2 to 659.1 mg kg^{-1} at 0–7.5 cm, from 461.5 to 531.4 mg kg^{-1} at 7.5–15 cm, and TP stocks ranged from 861.3–1,041.7 kg ha^{-1} for 0–15 cm (**Tables**

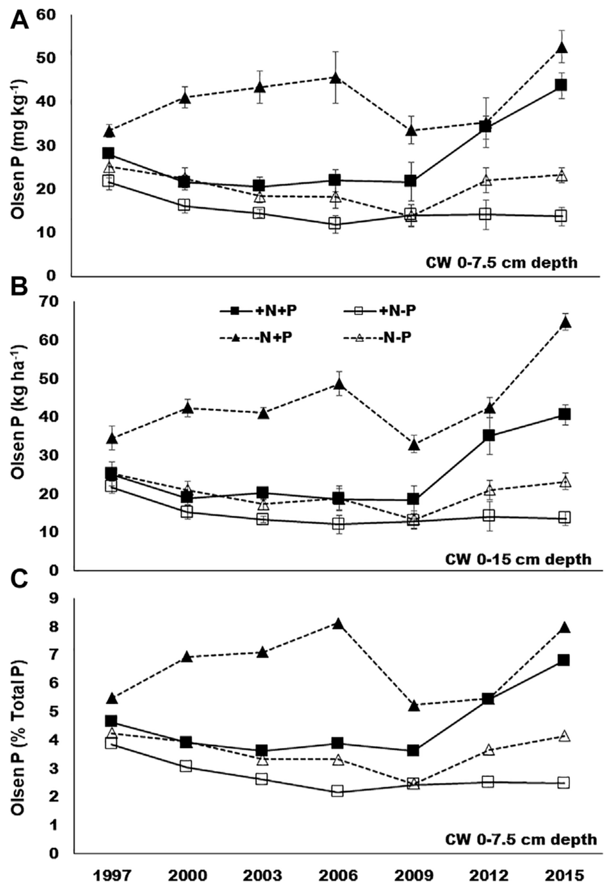

FIGURE 2 | Olsen P concentrations significant year*treatment interaction with ANOVA, for the continuous wheat (CW) rotation. Values are means ± standard error. **(A)** Olsen P concentration (mg kg^{-1}), 0–7.5 cm depth; **(B)** Olsen P concentration (kg ha^{-1}), 0–15 cm depth; and **(C)** Olsen P concentration as a percentage of total P concentration, 0–7.5 cm depth. Statistically significant differences among means (Tukey HSD; α = 0.05) are shown in **Supplementary Table S7**.

1–4). For all rotations, soil TP concentrations in the treatments fertilized with P were significantly greater than those for the treatments without P at 0–7.5 cm depth. For the FWW rotation, TP concentrations for the treatments not receiving any P from 1967 (N only and None) were significantly lower than all other treatments at 0–7.5 cm. There were significant differences in TP concentrations among years for all rotations for all depths, but there are no clear patterns by year (**Supplementary Tables S3–S5**). The means per year were calculated as the average for all treatments for each rotation within that year, despite the wide range in TP values among treatments. As such, caution should be used when comparing among years for each rotation, and the results are included with the Supplemental Materials for reference only. The main manuscript will focus on differences among treatments, and on the net change over time for each treatment for each rotation, on a kg ha^{-1} basis. For the FWW rotation, the net change in TP stock was positive for the +N+P, -N+P and -N-P rotations, indicating increased P concentrations over time, and was negative for the +N-P, N only and None treatments, indicating a net loss. However differences were only significant between the -N+P and N only treatments (**Table 1**). For the CW rotation, the net change in TP stock was negative only for the -N-P treatment, with significant differences only between the -N+P and -N-P treatments (**Table 2**). For the FW rotations, the net change in TP stock was positive for both treatments, and not significantly different (**Table 3**), while for the WL rotation the net change in TP stock was negative, but with no significant difference between treatments.

Soil Organic P

There were no significant interactions of treatment*year for Org P (mg kg^{-1}, 0–7.5 cm and 7.5–15 cm; kg ha^{-1}, 0–15 cm) for the FWW, CW and WL rotations, but there were significant interactions for the FW rotation (**Supplementary Table S2**). For the FWW rotation, there were no significant differences among treatments at either depth for mean Org P concentrations or mean Org P stocks (**Table 1**). When Org P was expressed as % TP, at 0–7.5 cm it was significantly higher in the N only, None and +N-P treatments than -N+P and +N+P and there were no significant differences among treatments at the 7.5–15 cm depth. The net change in Org P stock was positive for all treatments, with no significant differences among treatments. There were significant differences in Org P with year (**Supplementary Table S3**), but as noted for TP, there are no clear trends.

In the CW and WL rotations, there were no significant differences among treatments for mean Org P as concentrations or as % TP at either depth or for Org P stocks at 0–15 cm (**Tables 2**, **4**). There were significant differences with year for the CW rotation for all Org P pools, but no clear trends (**Supplementary Table S4**), and the net change in Org P stock was positive for all treatments (**Table 2**). For the WL rotation, there were no significant differences with year for any Org P pools, and the net change in Org P stock was negative for WL (**Table 4**; **Supplementary Table S4**).

For the FW rotation, there were significant treatment*year interactions for Org P concentrations at 0–7.5 cm, Org P stock at 0–15 cm, and for Org P (% TP) for both depths (**Supplementary Table S2**). At 0–7.5 cm, Org P concentrations were significantly higher in the 2010 +N-P soils than in the 2016 +N-P soils (**Table 5**). At the 7.5–15 cm depth, there were no differences between treatments for concentration but as a proportion of TP values were significantly higher in 2012 +N-P soils than the 2014 +N-P soils and the 2016 +N+P soils (**Table 5**). The net change in Org P stock was negative for the +N+P treatment and positive for the +N-P treatment, but the differences were not statistically significant (**Table 3**).

Soil Olsen P

There were significant treatment*year interactions for ANOVAs of Olsen P concentrations in mg kg^{-1} or as % TP for the 0–7.5 cm and 7.5–15 cm depths for the FWW rotation and for the 0–7.5 cm (mg kg^{-1} and as % TP) and for Olsen P stocks (kg ha^{-1}) at 0–15 cm for the CW rotation, but no significant treatment* year interactions for Olsen P for the FW and WL rotations

TABLE 6 | Grain and straw yield, grain and straw nitrogen (N) and grain and straw phosphorus (P), analyzed by fertilization treatment. Rotations are fallow-wheat-wheat (FWW), continuous wheat (CW), fallow-wheat (FW) and wheat-lentil (WL). Different letters for treatments within each rotation indicate significant differences (α = 0.05); *n* = 126 for FWW; *n* = 63 for CW and *n* = 24 for FW and WL (wheat and lentil).

Rotation	Treatment	Grain yield Mg ha^{-1}	Straw yield Mg ha^{-1}	Grain N kg ha^{-1}	Grain P kg ha^{-1}	Straw N kg ha^{-1}	Straw P kg ha^{-1}
FWW	+N+P	2.75 a (0.09)	4.77 a (0.16)	68.4 a (2.13)	11.4 a (0.37)	20.0 a (0.90)	2.31 a (0.13)
	+N-P	2.61 a (0.08)	4.15 ab (0.15)	64.8 a (2.03)	10.2 ab (0.32)	17.3 a (0.82)	1.71 b (0.11)
	-N+P	2.17 bc (0.09)	3.42 cd (0.18)	47.5 b (2.10)	9.37 cd (0.37)	10.7 b (0.62)	1.86 b (0.11)
	-N-P	2.02 c (0.09)	3.10 cd (0.18)	44.5 b (2.16)	8.42 cd (0.34)	10.5 b (0.68)	1.54 bc (0.11)
	N only	2.38 ab (0.07)	3.67 bc (0.13)	62.9 a (1.88)	8.15 cd (0.27)	17.2 a (0.70)	1.19 cd (0.07)
	None	1.98 c (0.07)	2.87 d (0.11)	48.1 b (1.83)	7.44 d (0.24)	11.1 c (0.54)	1.05 d (0.06)
CW	+N+P	2.44 a (0.10)	3.97 a (0.17)	59.7 a (2.28)	10.8 a (0.41)	18.0 a (1.14)	2.42 a (0.22)
	+N-P	2.08 b (0.08)	3.42 b (0.15)	51.5 b (2.25)	8.21 b (0.37)	16.3 a (0.91)	1.67 b (0.14)
	-N+P	1.58 c (0.06)	2.09 c (0.08)	33.1 c (1.26)	7.68 b (0.30)	6.59 b (0.27)	2.03 ab (0.14)
	-N-P	1.45 c (0.07)	1.92 d (0.10)	31.7 c (1.92)	6.93 b (0.36)	6.29 b (0.40)	1.49 b (0.11)
FW	+N+P	3.33 (0.14)	5.57 (0.32)	73.8 (3.17)	12.7 (0.69)	18.6 (1.35)	2.15 (0.25)
	+N-P	3.04 (0.16)	4.95 (0.38)	69.1 (3.34)	11.7 (0.76)	16.0 (1.47)	1.69 (0.21)
WL wheat	+N+P	3.51 (0.27)	5.57 (0.55)	90.2 (6.89)	15.4 (1.22)	21.1 (1.85)	2.94 (0.39)
	+N-P	3.24 (0.24)	4.62 (0.46)	80.5 (5.93)	13.9 (1.11)	19.7 (3.48)	2.46 (0.41)
WL lentils	-N+P	2.22 (0.26)	4.04 (0.39)	85.2 (10.3)	8.59 (1.00)	47.4 (5.70)	4.41 (0.58)
	-N-P	2.44 (0.25)	3.80 (0.28)	92.9 (9.69)	9.09 (0.95)	40.2 (4.37)	3.51 (0.40)

(**Supplementary Table S2**). In the FWW rotation, Olsen P concentrations for the N only and None treatments were below 10 mg kg^{-1} and were generally lower than for the other treatments at 0–7.5 cm depth, especially from 2006 to 2015, when concentrations for the +N+P and -N+P treatments were 25–35 mg kg^{-1} (**Figure 1A**; **Supplementary Table S6**). At 7.5–15 cm, there were no significant differences among treatments from 1997 to 2009, with concentrations below 10 mg kg^{-1} (**Figure 1B**; **Supplementary Table S6**). However, in 2012 and 2015, Olsen P concentrations for the N only and None treatments were significantly lower than other treatments at 7.5–15 cm depth. When expressed as % TP, trends were similar to those for concentration (mg kg^{-1}) for both depths (**Figures 1C,D**; **Supplementary Table S6**). Olsen P stocks (0–15 cm) ranged from 9.80 to 34.7 kg ha^{-1}, with significant differences among most treatments (**Table 1**). The net change in Olsen P stocks was positive for all but the +N-P treatment and was significantly higher in the +N+P and -N+P treatments relative to other treatments (**Table 1**).

For the CW rotation, Olsen P concentrations at 0–7.5 cm were similar for all treatments in 1997, were generally greater for the -N+P treatment than other treatments from 2000 to 2009 and then were significantly greater in -N+P and +N+P than in the +N-P and -N-P treatments in 2012 and 2015 (**Figure 2A**; **Supplementary Table S7**); similar trends could be seen for Olsen P stocks (0–15 cm) and as % TP for 0–7.5 cm (**Figures 2B,C**; **Supplementary Table S7**). At 7.5–15 cm depth, Olsen P concentrations (mg kg^{-1} or % TP) were significantly higher in the -N+P treatment than the other treatments (**Table 2**). The net change in Olsen P stocks was negative for the treatments without P fertilization and positive for treatments with P fertilization (**Table 2**).

For the FW and WL rotations, Olsen P concentrations (mg kg^{-1} and % TP) were significantly higher in the +N+P treatment compared to the +N-P treatment at 0–7.5 cm but not 7.5–15 cm, and for 0–15 cm (kg ha^{-1}; **Tables 3, 4**). The net change in Olsen P stocks was positive for both the FW and WL rotations, but was significantly different between treatments only for the WL rotation.

Crop Yields and P Depletion

There were no significant treatment*year interactions in ANOVA for grain and straw yield or grain and straw N and P for any of the studied rotations (**Supplementary Table S8**). For the FWW rotation, grain and straw yields and grain and straw N concentrations were significantly higher for the treatments receiving N (+N+P, +N-P, N only) than for the treatments without N (-N+P, -N-P, None; **Table 6**). Stopping P fertilization reduced straw P but not grain P or yields in the +N-P treatment compared to the +N+P treatment, but there were no significant differences in yield or grain and straw P for the -N-P treatment versus the –N+P) treatment. Grain and straw P concentrations were lowest in treatments not receiving P from 1967 (N only, None). There were significant differences by year for yield and grain and straw N and P concentrations, with lowest yields and concentrations in cumulative year 2003 and 2009 (**Supplementary Table S9**). These cumulative years include the years with lowest total precipitation, in 2001, 2007 and 2009 (**Supplementary Figure S1**). Both mean and cumulative P depletion (the difference between P removed in grain and P added in fertilizer) were negative for the -N+P treatment, and were positive for other treatments (**Table 1**). This indicates that less P was removed in grain than was added with fertilizers for the –N+P treatment, but not for other treatments. Both mean and cumulative P depletion were significantly higher in treatments without P (+N-P, -N-P) than for the corresponding treatments with P (+N+P, -N+P).

In the CW rotation, grain and straw yields were significantly higher in the +N+P treatment, and were lowest in the treatments without N, regardless of P fertilization (**Table 6**). Cessation of P fertilization reduced grain and straw P concentrations for the +N-P treatment compared to the +N+P treatment, but did not significantly reduce grain and straw P in the treatments without N. Similar to the FWW rotation, on a yearly basis yields were generally lower in years with low precipitation (**Supplementary Table S9**). Mean and cumulative P depletion were negative only for the -N+P treatment, and P depletion was significantly higher in the treatments in which P fertilization stopped in 1995 compared to treatments with continued P fertilization (**Table 2**).

There were no significant differences with treatment for grain and straw yield or grain and straw N and P for the FW rotation or for either wheat or lentils in the WL rotation (**Table 6**; **Supplementary Table S8**). Generally, grain and straw yields were higher in cumulative year 2012 than 2016 (**Supplementary Table S10**), again reflecting differences in precipitation among years (**Supplementary Figure S1**). For the FW rotation, both mean and cumulative P depletion were positive, and were significantly higher for the +N-P treatment than +N+P treatments (**Table 3**). For the WL rotation, mean P depletions for wheat and lentils and the cumulative P depletion were significantly higher for the +N-P treatment than the +N+P treatment, and mean P depletion was negative for the lentil +N+P treatment, but was otherwise positive (**Table 4**). Both N and P fertilizers were added for the wheat phase but only P was added for the lentil phase of the +N+P treatment; the negative P depletion with lentil indicates P was accumulating with lentil because more P was added with fertilizer than was removed with the crop.

DISCUSSION

Phosphorus Accumulation With Fertilization

For the rotations of this study, the total amount of P applied to the plots receiving P (+N+P or -N+P) decreased in the order CW (10 kg P ha^{-1} yr^{-1} annually from 1967) > WL (10 kg P ha^{-1} yr^{-1} annually from 1982 for both phases of the rotation) > FWW (10 kg P ha^{-1} yr^{-1} for two of three phases of the rotation from 1967) > FW (10 kg P ha^{-1} yr^{-1} in alternate years from 1982). From 1995 to 2015 for the FWW and CW rotations, the net changes in TP (TP Δ) and Olsen P (Olsen P Δ) were positive for both treatments with P fertilization (+N+P, -N+P). For the FW and WL treatments from 2008 to 2016, both TP Δ and Olsen P Δ were positive for the FW +N+P treatment, but only Olsen P Δ was positive for the WL +N+P treatment; TP Δ was negative for that treatment. The net changes in Org P (Org P Δ) were positive for both +N+P and -N+P in CW and FWW, but were negative for +N+P for FW and LW.

In 1995, the highest Olsen P concentrations for treatments in the CW and FWW rotations were ~30 mg kg^{-1} at 0–7.5 cm depth (**Figures 1A**, **2A**). As such, the P application rate of 10 kg P ha^{-1} yr^{-1} was within the recommended rates for spring wheat in the Brown soil zone, to replace P removed in harvested crops and to maintain soil test P concentrations (McKenzie and Middleton, 2013; Government of Saskatchewan, 2022). The positive TP Δ and Olsen P Δ stocks for the treatments with P fertilization in the FWW and CW rotations indicate that continued P applications supplied more P than was required to maintain soil test P concentrations in these soils, consistent with other studies (Cade-Menun et al., 2017). This also highlights the importance of fertilizing based on soil tests rather than at a flat annual rate, because Olsen P concentrations after 2009 indicate that soil test P concentrations are adequate for crop needs, with no agronomic or economic benefit from additional P fertilization (**Figures 1A**, **2A**).

The TP Δ and Olsen P Δ were particularly high for FWW and CW plots fertilized with P but not N (-N+P), which were the only treatments for these rotations with negative mean and cumulative P depletion, indicating net accumulation rather than depletion. Build-up of TP and Olsen P concentrations when P is applied without N was previously reported in these soils for data to 2005 (Selles et al., 2011) and world-wide, including long-term experiments applying P and or potassium but not N in England (Syers et al., 2008) and China (Khan et al., 2018). Without adequate N fertilization, crop growth is poor, which in turn reduces P uptake, leaving fertilizer P to accumulate in soils. This in turn increases the risk of P loss in runoff or erosion. While presumably most producers applying chemical fertilizers would apply both P and N at locally-recommended rates, application of manure could potentially over-supply P relative to N in a similar fashion to the results here, because the ratio of P relative to N in most manures is higher than plant requirements (Eghball et al., 2002; Khan et al., 2018).

For the +N+P treatments for all rotations, mean and cumulative P depletions were positive, which is consistent with the low or negative P balances for Saskatchewan determined by Reid and Schneider (2019). Depletion of P was calculated solely from grain removal and fertilizer inputs, which is the difference method used to determine P use efficiency (Syers et al., 2008; Selles et al., 2011; Chien et al., 2012). This method does not factor in residual or legacy P remaining in the soil from previous fertilizer applications, which clearly underestimates the P available to, and used by, plants in these soils (Selles et al., 2011; Chien et al., 2012). Indeed, the cumulative P depletions calculated for +N+P treatment for the FWW, CW and FW rotations are contrary to the positive TP Δ and Olsen P Δ for this treatment in these rotations. For the CW -N+P treatment, P depletion was negative, indicating P accumulation, which is similar to Olsen P Δ (Olsen P Δ 30.3 kg ha^{-1}; cumulative P depletion -35.6 kg ha^{-1}), both of which were much lower than TP Δ for that treatment (159.6 kg ha^{-1}). Only the +N+P treatment for the WL rotation showed a negative TP Δ concentration that was comparable to the calculated cumulative P depletion (TP Δ −25.4 kg ha^{-1}; cumulative P depletion 26.2 kg ha^{-1}), although Olsen P Δ was positive. This may be due to differences in crop uptake and removal for lentils and wheat in this rotation compared to the other wheat-only rotations, or it may reflect the shorter time period of study in that rotation compared to CW and FWW rotations; further investigation is warranted. These variations among rotations highlight the need for caution and field-scale testing when applying broad scale P balance calculations in modelling to develop policies for P management (Reid and Schneider, 2019).

Concentrations of Org P at both depths and Org P Δ were not significantly different for treatments with and without P for the FWW, CW and WL rotations. There were significant treatment*date interactions in ANOVAs for Org P for the FW rotation. However, there were no significant differences among dates for the treatment with P fertilization (+N+P) for any Org P pool. For the FWW rotation, Org P (% TP) was significantly lower in treatments with P fertilization compared to those without. This indicates that Org P concentrations in P-fertilized soils in that rotation remained steady, while soil TP and inorganic P concentrations increased from inorganic P in fertilizer; this also demonstrates that fertilizer P accumulated in soils with continued application.

It was hypothesized that concentrations of Olsen P, TP and Org P would increase with continued P fertilization for all crop rotations. Positive concentrations of TP Δ and Olsen P Δ for the FWW, CW and FW rotations and for Olsen P Δ for the WL rotation with +N+P and -N+P treatments generally support this hypothesis with respect to Olsen P and TP. However, Org P Δ was positive for FWW and CW and negative for FW and WL, indicating that it did not consistently increase with P fertilization. It was also hypothesized that Olsen P concentrations would change more with continued fertilization than TP and Org P concentrations, but Olsen P Δ stocks were lower than TP Δ and Org P Δ with continued P fertilization for all but the WL rotation. This suggests that applied P fertilizers do not remain in the labile P pool extracted with bicarbonate for Olsen P, and are instead converted into less labile pools.

Phosphorus Drawdown With Fertilizer Cessation

In the FWW rotation, Org P Δ and Olsen P Δ for 1995–2015 were positive after P cessation in 1995 (+N-P and -N-P treatments), and for plots not receiving any P fertilizer from 1967 (N only and None treatments); however, TP Δ was positive only for the -N-P treatment. In contrast, in the CW rotation, TP Δ was negative for the -N-P treatment and positive for the +N-P treatment, while Org P Δ was positive for both treatments and Olsen P Δ was negative for both treatments where P fertilization stopped (+N-P, -N-P). The mean and cumulative P depletions were positive for all FWW and CW treatments without P fertilization after 1995. For the FW and LW rotations, stopping P fertilization in 2008 (the +N-P treatment for both rotations) produced positive results for FW TP Δ, FW Org P Δ and FW and LW Olsen P Δ, but negative results for LW TP Δ and LW Org P Δ. In both the FW and WL rotations and for both lentils and wheat in the WL rotations, mean and cumulative P depletions were positive. For all rotations, mean and cumulative P depletions were significantly higher in treatments without P fertilization compared to continued P fertilization, regardless of N fertilization.

These results indicate that stopping P fertilization reduced soil TP and Olsen P compared to treatments with continued P fertilization, which is consistent with the results for P fertilizer cessation studies from other regions, including Denmark (Rubæk et al., 2013), Ireland (Cade-Menun et al., 2017), Germany (Medinski et al., 2018), Canada (Liu et al., 2019), and with a global data set (Appelhans et al., 2020). Drawdown was greater in FWW and CW treatments fertilized with N (+N-P) than without N (-N-P), where greater crop growth would have increased P uptake. This is reflected in greater grain yields and grain P for +N-P than -N-P treatments for CW and FWW. All of these results support the belief that stopping P fertilization is a simple and effective way to draw down high concentrations of soil test P and TP (Rowe et al., 2016; Withers et al., 2019). And although the current study did not measure P losses through erosion or runoff, a similar drawdown study in the neighboring province of Manitoba showed that P in runoff was reduced by P fertilizer cessation (Liu et al., 2019), suggesting that similar results would occur for the plots of this study and elsewhere on the Canadian prairies.

Two concerns for producers with P fertilizer cessation are potential yield reductions and the time required to drawdown soil P concentrations (Withers et al., 2019). For the FWW and CW rotations, no significant differences in Olsen P stocks (kg ha^{-1}; 0–15 cm) were detected by 2005 in +N-P treatments compared with +N+P plots (Selles et al., 2011), consistent with the results of the current study. However, significant differences between the +N+P and +N-P treatments were observed in TP and Olsen P stocks with additional years without P fertilization, particularly after cumulative year 2009 for both rotations (**Figures 1**, **2**). Olsen P and TP concentrations were also significantly reduced after 8 years without fertilization for the FW and LW rotations. This is comparable to Olsen P drawdown after 7 years in croplands in Manitoba, Canada (Liu et al., 2019), but was longer than for grasslands in Ireland, in which Olsen P concentrations were significantly reduced after only 5 years (Cade-Menun et al., 2017). These differences are most likely due to differences in vegetation and rainfall. With respect to yield reductions, Selles et al. (2011) reported no significant differences in yield and grain P with and without P fertilization for FWW with N fertilization up to 2005, which is consistent with the results to 2015 for the same plots. Yields and grain P concentrations were also not significantly reduced after 8 years without P fertilizers in the FW and WL rotations. In contrast to the other rotations, significant differences in yield between the +N+P and +N-P treatments for the CW treatment were observed in 2005 by Selles et al. (2011), and by 2015 in the current study. However, as noted by Selles et al. (2011) and by Liu et al. (2015) in another study on these plots, while significant differences are seen over the whole study period, on a year-by-year basis there are no significant differences in yields for many years, especially in dry years when precipitation limited crop growth regardless of fertilization (Selles et al., 2011). Summer fallow is used to conserve moisture on the Canadian prairies, which could be why yields were less affected by fertilization in the FWW rotations (Chen et al., 2021). These results suggest that P fertilizer cessation for short (5–10 years) time periods could reduce high soil P concentrations with little effect on yield as long as N fertilization is maintained (McKenzie et al., 1992; Selles et al., 2011), especially in drought years when moisture conditions will reduce plant growth.

It is clear from this study that crops in these soils can find some P to maintain growth, even for plots with no P fertilization since establishment in 1967 (the FWW N only treatment). This study only sampled soil from the surface 0–15 cm; however, plant roots can access P from deeper soil depths (Bowman and Halvorson, 1997; Selles et al., 2011). For these rotations, only grain was removed, with straw and roots left on plots after harvest. The predominant P form in this residual plant material is phosphate (Noack et al., 2016), which will be returned to the soil after decomposition of organic matter. A high proportion of the total P in these soils is organic P (48%–65% TP), which previous studies of these plots have shown to include a range of organic P compounds including inositol hexaphosphate stereoisomers (Liu et al., 2015; Chen et al., 2021). Other studies of P fertilizer cessation, including in a corn-based cropping system in Ontario, Canada (Zhang et al., 2020) have shown reductions in organic P, indicating that this is a source of phosphate to crops after fertilizer cessation. However, in the rotations of the current study, organic P as a proportion of total P was either not significantly different in plots with P fertilizer cessation (FWW, CW, WL) or was significantly higher than plots with continued P fertilization (FW rotation), suggesting that plants on these plots were not obtaining phosphate from mineralizing organic P.

Factors Affecting P Cycling in These Soils

Long-term experiments such as this make the assumption that all factors influencing nutrient use by crops remain constant in these plots, with the only changes being the N and P fertilizers added or the P fertilizer withdrawn. However, that is not the case; there will be annual variation in some factors and long-term changes in others. As the data for this study show, in rain-fed systems annual precipitation, including both drought and flooding, will significantly alter crop growth, P uptake and P cycling (McKenzie et al., 1992; Selles et al., 2011; Khan et al., 2018). There will also be variations with crop health, including crop diseases, insect and hail damage, etc., which will alter plant growth and nutrient uptake. And on the plots of this study, long-term N fertilization with NH_4NO_3, urea and/or MAP has significantly decreased soil pH, from ~ 7 in CW -N-P plots to < 6 in CW, FWW and WL +N+P plots (Li et al., 2020; Chen et al., 2021; B. Cade-Menun unpublished data). This pH change will alter soil cations, reducing exchangeable calcium and magnesium and increasing exchangeable aluminium and iron and changing the sorption and precipitation of P compounds with these cations (Liu et al., 2015; Chen et al., 2021). It will also alter the soil microbial community and the production of enzymes that mineralize organic P (Li et al., 2020; Chen et al., 2021). This could make legacy P less available to crops, increasing P deficiencies after fertilizer cessation.

CONCLUSION AND RECOMMENDATIONS

Cessation of P fertilization has been shown in many parts of the world to draw down legacy P concentrations to agronomically-optimal levels to reduce the potential for P loss, and this is supported by the results of this study. On a short-term basis this can be done with little to no effect on yields, and is best achieved when there are no other factors limiting crop growth, including deficits in moisture or other nutrients. However, the results of the current study also indicate that the rate of P draw down will vary among crops, and among different rotations of the same crop. The results of this study also show that legacy P will accumulate even with fertilization at locally recommended rates, which suggests that fertilizer guidelines may need to be revised, to minimize environmental impacts from soil P accumulation and to more efficiently use the finite rock phosphate used to produce chemical P fertilizers.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

BC-M was responsible for all aspects of this manuscript.

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CONFLICT OF INTEREST

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/sjss.2022.10737/full#supplementary-material

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REVIEW
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Land Recovery and Soil Management with Agroforestry Systems

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Soils have many ecological functions and provide various ecosystem services including support for global food and fuel production. However, FAO reports indicate that approximately one-third of the planet's arable lands show levels of degradation from processes including soil erosion, low levels of nutrients, acidification, salinization, compaction, sealing, and contamination. These conditions are also found in Brazil where soil degradation is largely caused by inadequate land management. Worldwide, strategic policies have been presented to mitigate this problem, with emphasis on sustainable agriculture. Among them, agroforestry has been identified as a viable system for mitigating and recovering degraded areas. Agroforestry techniques have been developed and tested but are still not understood by farmers, due to their complexity. This study aimed to analyze experiences and studies with agroforestry reported from Australia, some countries in Africa, and Brazil to search for similarities in these complex systems and identify possible correlations to support the hypothesis that land recovery can be enhanced through soil management using agroforestry. A Sankey diagram was developed to illustrate relationships among problems, the adoption of agroforestry and improvements, and the most important contributions. Data analysis shows that the main problems related to soil degradation are soil erosion and decreased soil fertility, while the adoption of agroforestry systems proved to improve different aspects of soil quality and to be a safe path to sustainable agricultural production. To obtain more information on the adoption of these systems in different locations, soils, and climates, it is important to implement policies for reducing land degradation. Furthermore, the assessment of the economic, environmental and social benefits of improving soil fertility and decreasing erosion in agroforestry systems is necessary to validate the use of agroforestry as a sustainable agricultural practice.

Keywords: soil recovery, sustainable development, food security, soil resources, Millennium Development Goals

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INTRODUCTION

Soil is essential for the maintenance of life on the planet, especially for living beings in terrestrial biomes and ecosystems. Among the many functions of soil, its use in food production and for storage and conservation of drinking water are closely related to human life (FAO and ITPS, 2015). One of the objectives of the 2030 Agenda, in relation to the Millennium Challenges established by the United Nations (UN), is to "Protect, recover and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, stop and reverse land degradation, and halt the loss of biodiversity." To achieve this goal by 2030 it is essential "to act against desertification and restore degraded land and soil, including land affected by desertification, droughts, and floods, and to seek for a world neutral in terms of soil degradation" (UNIC Rio, 2016).

Recent FAO reports show that approximately one-third of the planet's arable land is already degraded (FAO, 2022), indicating the urgent need to recover or remedy the damage caused by inappropriate agricultural practices and other factors. Therefore, strategic policies that reinforce the adoption of sustainable agricultural practices are essential to ensure food production and soil conservation. The growth in world population increases demand for food and fuel, impacting productive lands and intensifying the use of current agricultural areas and soil degradation (Hartemink et al., 2008).

The Global Assessment of Soil Degradation (GLASOD) project, which began in the late 1980s, affirmed that soil degradation was caused by "water and wind erosion, loss of nutrients and organic matter, salinization, acidification, pollution, compaction, and physical degradation, waterlogging, and subsidence of organic soils." Similar processes and factors are highlighted by the FAO's Status of the World's Soil Resources report (FAO and ITPS, 2015).

Understanding the environmental problems faced and the means of production are crucial to developing knowledge about food cultivation in biodiverse systems. There are multifunctional indications that agroforestry systems have positive effects in terms of effectively sequestering carbon, enriching soil, conserving biodiversity, and improving air and water quality, which benefit society as a whole (Jose, 2009).

Agroforestry Systems (AFS) are integrated systems involving trees and agricultural and/or animal crops, simultaneously or sequentially, with the objective of sustainably increasing the total productivity of plants and animals per unit of area (Nair, 1985). Another concept that agroforestry comprises land-use systems and technologies in which woody perennial plants (trees, shrubs, palms, or bamboos) and agricultural or animal crops are cultivated on the same plot organized in planned spatial and temporal arrangements (Mosquera-Losada et al., 2012; Nair and Garrity, 2012; Catacutan et al., 2017 apud (FAO and ICRAF, 2019). According to these authors, biodiverse and interactive production systems provide social and ecological benefits. Among them, this study highlights increased soil fertility, control of soil erosion, water regulation, carbon sequestration, biodiversity, and resilience to natural disasters.

Agroforestry has been recognized as a viable system for mitigating land degradation and assisting in its recovery. A range of plant species are used to form a biodiverse agricultural composition in contrast to monocrop systems. In general, agroforestry systems are composed of a diverse mix of trees, crops and herbaceous, and forage species, in which the presence of trees is a requisite. This composition increases biodiversity and local ecosystem services and functions, leading to sustainable rural development, with many environmental and economic benefits. However, farmers may see the planting of trees negatively, due to their occupation of land and reduction of areas for food production (Leakey et al., 2015). Thus, it is necessary to evaluate and consider different forms of local arrangements and compositions of agroforestry systems, which were not compared in this study.

The challenges related to the maintenance and conservation of the environment in relation to its use and exploitation have been discussed for years by the UN Millennium Development Goals (MDGs) and environmental conservations. Garrity (2004) and Leakey et al. (2015) have presented agroforestry options for mitigating environmental problems arising from conventional agriculture systems. Garrity (2004) indicated that the World Agroforestry Center (ICRAF) reported seven relevant aspects in the use of agroforestry to fulfill the MDGs, summarized as improving soil fertility and regenerating degraded lands, reducing poverty in rural areas by growing commercially viable trees, promoting health and nutrition of rural populations, conserving biodiversity, rewarding farmers who conserve watersheds with agroforestry systems, helping farmers access emerging carbon markets, and training people and research institutions in the implementation of agroforestry systems. In their study, Garrity concluded that there is growing use of and research on agroforestry and its environmental benefits in developed countries, and this could have a positive impact in developing countries, citing examples from southern African nations.

Another study that points to the environmental benefits of agroforestry systems involved an analysis of twelve agroforestry farms in Sweden that are recognized as using sustainable agriculture methods. In the cases analyzed, there was recognition that the knowledge and practices adopted by the farmers were sufficient for the development of agroforestry, but it was still seen as a method for enthusiasts. There is a clear need for more research to make the systems profitable, as well as legislative support (Schaffer et al., 2019).

This analysis of agroforestry applications in the southern hemisphere was prompted by the perception that research conducted in different locations would bring similar conclusions about the use of agroforestry and its effects in recovering degraded soils. There is substantial information on the relationship between the application of agroforestry systems and improved soil quality. However, results are different by region and climate, and studies show that the use of agroforestry is more efficient in tropical regions where nutrient cycling is more intense than in cooler regions (Miccolis et al., 2019). This became clear in studies by Rao et al. (1998) in which sub-Saharan Africa provided more conclusive data regarding agroforestry applications than places such as tropical Asia and Latin America.

This study aimed to analyze research about agroforestry experiences as reported from Australia, African countries, and Brazil to identify similarities in these complex systems and possible correlations, to support the hypothesis that the application of agroforestry for soil management can enhance land recovery.

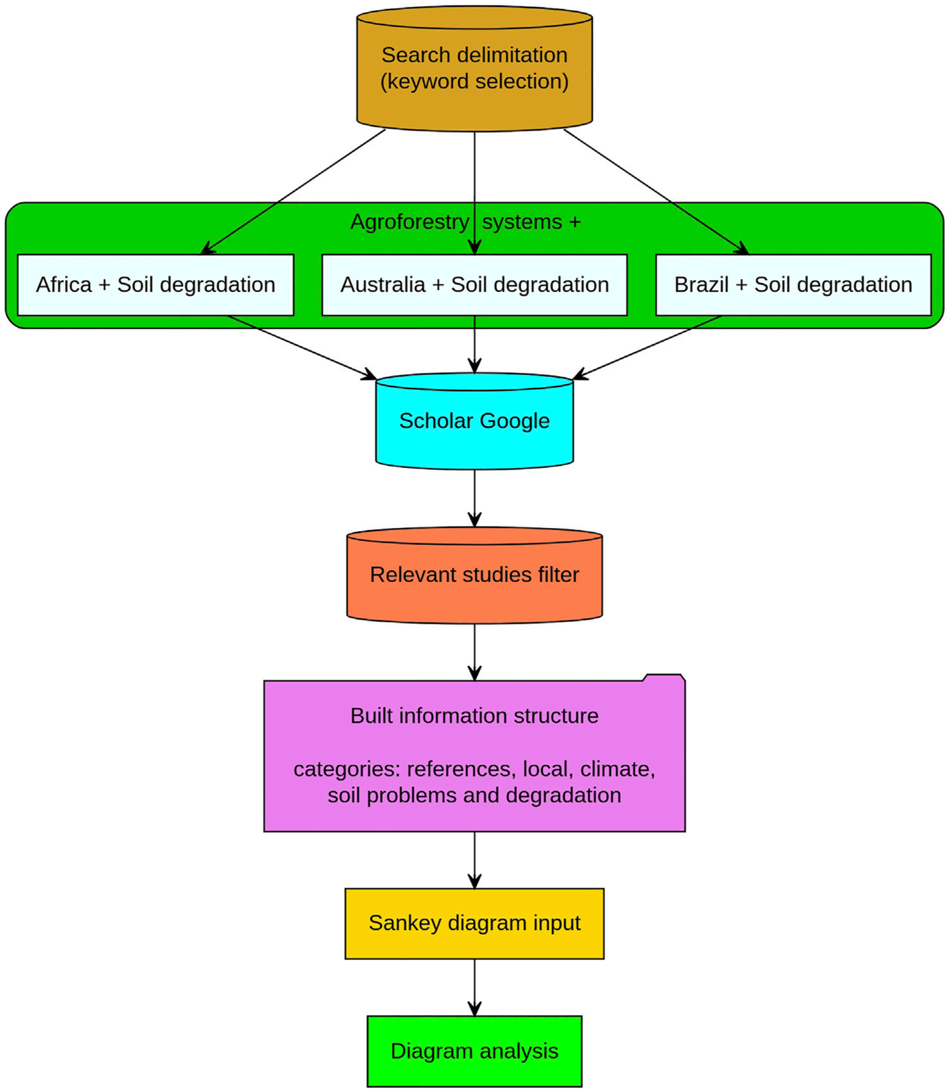

FIGURE 1 | Flowchart of methods applied.

MATERIALS AND METHODS

There is currently debate about ecosystem services and multifunctional agroforestry services, exploring the economic and environmental benefits related to biological, soil, and water conservation. This study focused on information about benefits to soil. The research was carried out using secondary sources to populate a database referring to local land degradation problems identified in the studies and the remediations found from the implementation of agroforestry. These problems and improvements are mentioned in reports by the Millennium Ecosystem Assessment and the International Assessment of Agricultural Science and Technology for Development (Chavan et al., 2016).

This research constructed a database focused on tropical areas. Scientific articles and technical studies were searched in the literature using the keywords: agroforestry, soil degradation, Brazil, Africa, and Australia. We also used the combinations: agroforestry plus soil degradation Brazil; agroforestry plus soil degradation Africa; and, agroforestry plus soil degradation Australia. These searches identified studies about the adoption of agroforestry systems for soil conservation and soil recovery and allowed analysis of the studies. Some studies with data on other locations and climates were maintained in the database for comparison (**Figure 1**).

The first step was to search papers about soil degradation problems and the implementation of agroforestry. Twenty studies were selected that show a strong relationship between soil degradation and the improvements obtained by applying agroforestry systems (**Table 1**). From these documents, information of interest was compiled to analyze possible connections between problems arising from poor soil

TABLE 1 | Relationship between author(s) and local(s).

Author(s)	Local(s)
Cooper et al. (1996)	sub-Saharan Africa
Rao et al. (1998)	sub-Saharan Africa; West Africa; tropical Asia; Latin America; India
Schembergue et al. (2017)	Brazil
Garrity (2004)	sub-Saharan Africa; South Africa; South Asia; China; Australia; Philippines; Brazil; North America; Europe
Jose (2009)	West African; Asia; Americas; Brazil; North America (California, Florida)
Webster (1997)	Africa; Europa; North America
Franzel (1999)	Africa (southern Cameroon, eastern Zambia, western Kenya)
Leakey et al. (2015)	Africa [Cameroon, Nigeria]
Nuberg (1998)	Australia
Baudry et al. (2000)	Europe; Africa; Bolive; Equador; Asia
Amador (2003)	Brazil
Costa et al. (2015)	Brazil
Costa et al. (2013)	Brazil; (São Paulo)
Zomer et al. (2016)	sub-Saharan Africa; South Africa; South Asia; China; Australia; Philippines; Brazil; North America; Europe
Mbow et al. (2014)	Africa
Luedeling et al. (2016)	sub-Saharan Africa; Australia; North America; Brazil; Europe
Schroth (1999)	Brazil (Bahia); South African; East Africa; Australia
De Souza et al. (2020)	Brazil
Kaba et al. (2021)	Africa [Ghana]
Santos et al. (2021)	Brazil

management, agroforestry, and land restoration. The database included data on: location (country and subregion); climate; year and title of the study; problems related to soil degradation; improvements found in the soil (from the application of agroforestry); and the author's main conclusions.

We analyzed the document—The Status of the World's Soil Resources (FAO and ITPS, 2015) using the keywords and subjects described above along with expressions such as: soil erosion by wind and water; organic matter decline; compaction; salinization; and landslides and rock materials. More general qualitative indicators and terms were used to identify problems and/or soil remediation. This study was designed as a qualitative evaluation of practices to restore degraded soils by adopting agroforestry systems.

After the database was compiled, the following rules were used to analyze soil degradation: search category "problems related to soil degradation" using the keywords acidification, compaction, desertification, erosion, fertility, leaching, and salinity; and search with keywords related to "soil improvements" including carbon sequestration, compaction, climate change, erosion, fertility, microclimate, nutrients, organic matter, soil carbon, water.

A Sankey diagram (Kennedy and Sankey, 1898) illustrates the flow of transformation, with the width of the lines representing the flow rate. It has been used to represent land cover and change of land use (Cuba, 2015). In this study it was selected to show the relationship between soil problems, the adoption of agroforestry, soil quality improvements, and relevant contributions.

RESULTS

The Sankey diagram prepared helps to understand the cross-referencing information presented as output, in which the relationships express the links between the "Reference," "Climate," and "Problems," passing through "System (Agroforestry)," and resulting in the "Improvements," as shown in **Figure 2**.

In the Sankey diagram, the width is proportional to the quantity represented, so thicker lines indicate a higher frequency of occurrences. For instance, thicker lines emerging from the authors—"Reference," indicate that the study has more information, which could mean that there were more study locations, or that it presents more problems or improvements. The most common factors in soil degradation are erosion and fertility, followed by losses from nutrient leaching and increased salinity, while desertification and compaction are at a lower level. It is noteworthy that acidification was not presented as a soil degradation factor in the works selected for the study, consequently, it is not in the diagram. One reason may be that most of the weathered soils in tropical regions already have high natural acidity, expressed by low pH values or high aluminum contents. In tropical environments, soils commonly have low levels of nutrients and low pH, leading to aluminum toxicity, and these properties are exacerbated in degraded soils as a result of overgrazing, large-scale mechanized agriculture, and extensive and frequent use of fire as a tool for removal of vegetation and pasture management. Changing land use towards more sustainable practices such as agroforestry can improve soil structure and fertility (Miccolis et al., 2019).

In terms of research that analyzed the effects of agroforestry in the different regions, studies by Rao et al. (1998) and Luedeling et al. (2016) were highlighted in this analysis. These studies are broad reviews of the adoption of agroforestry systems. They do not focus on specific contributions but point out the benefits of agroforestry to soil quality including those observed by farmers.

Problems of soil fertility deterioration and soil erosion were the most cited in the studies included in the database. These problems are related since soil's loss of productive capacity due to low soil fertility increases with the loss of surface soil layers due to

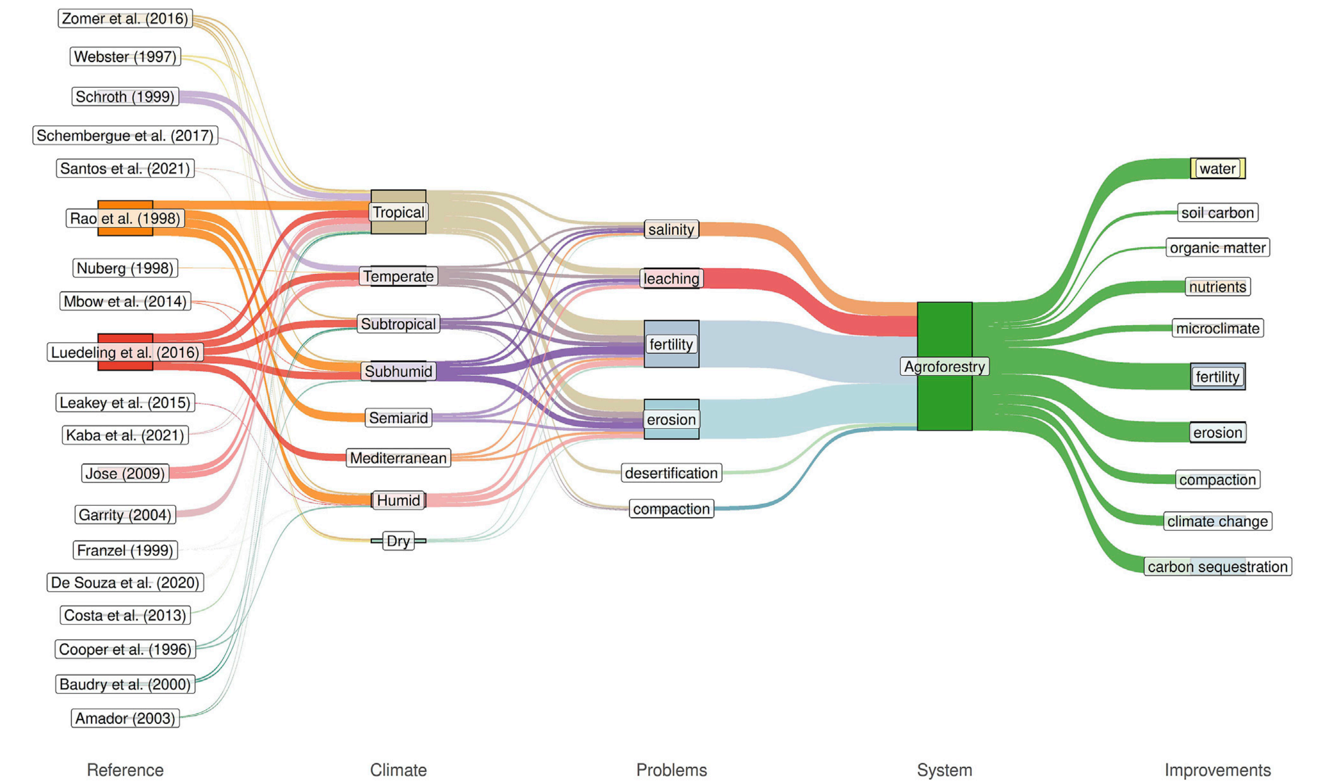

FIGURE 2 | Relationships among soil problems, adoption of agroforestry systems and soil health amelioration expressed in a Sankey diagram.

erosion, both by water and wind, as well as the improper use of tillage machinery. These results corroborate the indication of agroforestry to improve soil quality both in terms of fertility and erosion, as can be seen by the keywords fertility and erosion highlighted (thick lines) in the Sankey diagram. For this parameter of the analysis, the keyword water also stood out, indicating benefits from agroforestry systems including improvements to water infiltration, and reestablishment of the hydrological cycle.

Information on soil problems and improvements in the different studies is mainly from regions with tropical climates, due to the initial selection of countries. However, some of the broader studies on the adoption of agroforestry as a method for soil recovery and conservation have data from other climates, with an emphasis on temperate, subhumid, and humid regions (Feliciano et al., 2018).

The Sankey flow chart can be understood to first evaluate the information with the previously determined keywords (salinity, leaching, fertility, erosion, desertification, and compaction). Then, a search is conducted for these terms in the subsequent column, which indicates the improvements attained by the use of agroforestry. These include benefits such as remediation/mitigation/solutions/improvements to water, soil carbon, organic matter, nutrients, microclimate, fertility, erosion, compaction, climate change, and carbon sequestration. There are many more terms (words) in the process of improvement and transformations of the areas that use agroforestry and these improvements are related to one or more terms (words) from the column of problems. The terms used for problems are commonly cited in the field of soil science. The terms that appear after the use of agroforestry are all taken from the studies examined in this review study.

For instance, water erosion caused by exposed soil is reduced by increasing land coverage with biomass from pruning and plant growth, and recovery of soil structure due to influence from different root systems, which add organic carbon, positively affecting soil biodiversity, nutrient availability, soil fertility, and water retention capacity, etc. Just as the leaching of elements can be reduced by increasing soil organic carbon and improving the use of nutrients by the different plants in the agroforestry system. Soil organic carbon (SOC) storage is determined by the balance between the amount of carbon that enters a system, mainly through the addition of plant residues, and the amount that leaves the soil from mineralization, driven by microbial processes, and leaching out of the soil as dissolved organic carbon. Thus, the amount of SOC is affected negatively by erosion and positively by deposition and transformation of biomass into soil organic matter (FAO and ITPS, 2015).

In terms of locations, the region of Africa with the most weight in this research was sub-Saharan Africa, and, as a consequence of the study design, there is a concentration of works from Brazil and a small number for Australia. A considerable number of studies on this topic are found in North America, and other countries of Latin America, India, Europe, and China, etc.

However, they were not included in the main search, although their data was also addressed in the analysis of the use of agroforestry and its benefits. The list of authors and study locations are seen in **Table 1**.

DISCUSSION

There are many studies on locations with a tropical climate, as seen in **Figure 2**. This may be related to the ease of implementing agroforestry systems in environments with faster nutrient cycling, such as humid tropical regions, and because when designed as a climate change mitigation strategy, these agroforestry systems prove to be efficient for storing carbon in the ground (Feliciano et al., 2018). As analyzed by Cooper et al. (1996) much of the practice of combining trees with crops is based on the natural fallow and regeneration periods of some species in tropical regions of Africa, which led farmers to use them in other regions. This practice became known as enriched fallows, in which certain tree species are planted and maintained to help improve soil fertility. However, the practice is not limited to tropical climates, the use of agroforestry in both subhumid and humid climates is significant in this analysis.

Interactions in tropical agroforestry systems have been analyzed since the 1980s in these regions where hedgerow intercropping (HI) systems or alley cropping involves the growth of crops between hedgerows of regularly pruned tree species. HI systems improved soil fertility, promoted sustainable agriculture on nutrient-poor soils, and helped to control erosion on sloping lands (Rao et al., 1998).

The HI system was a propellant for the application of integrative agroforestry approaches in tropical regions. However, according to Rao et al. (1998), agroforestry is much more complex than annual intercropped systems, due to the unequal arrangement of the components, with dominant and perennial trees, making the systems continuous and not seasonal. Rao et al. (1998) state that tropical agroforestry research has emphasized technologies that utilize the service functions of trees that improve soil fertility and soil conservation. Garrity (2004) also identified the use of integrated agroforestry systems as a differential for small farmers in poor regions with low consumer market infrastructure, as in the tropical home gardens cited by Kumar and Nair 2004 apud Garrity (2004).

Regarding the effects of climate change on production systems, Schembergue et al. (2017) analyzed sites in Brazil to compare agroforestry and monoculture and found favorable conditions for crop adaptations with agroforestry systems, demonstrating that they can be viable alternatives for farmers affected by the negative effects of climate change on their agricultural production. The authors point to changes in both temperature and precipitation at sites that use agroforestry, showing their potential for adapting to changes in climate.

In this analysis, the studies that composed the Sankey diagram did not show significant relevance of agroforestry systems for the term climate change. However, this term is a recent research perspective in soil research and may become more relevant due to recent reports of the Intergovernmental Panel on Climate Change (IPCC). Feliciano et al. (2018) evaluated the benefits of agroforestry to mitigate climate change and concluded that there are not enough regional studies to prove the absorption of greenhouse gases by agroforestry. These gaps about the consequences of climate change can be seen in this study, in which the solutions pointed out by researchers and farmers are more focused on soil quality.

Agriculture production will increasingly need to deal with extreme events of drought and floods and finding means to adapt to climate variations may be crucial for small farmers. In Garrity's research, it is possible to observe two important roles for agroforestry to the Millennium Development Goals (MDGs) (Garrity, 2004). The systems are found to both mitigate the emission of greenhouse gases and allow crops to better adapt to environmental changes.

Other important contributions of agroforestry were analyzed by Jose (2009), Mosquera-Losada et al. (2012), Nair and Garrity (2012), Catacutan et al. (2017), and FAO and ICRAF (2019) who studied issues such as carbon sequestration, soil enrichment, biodiversity conservation, and air and water quality improvement for landowners, farmers and society at large.

Concerning the inherent problems that affect the use and exploitation of soil without conservation practices, higher concentration of information was found about the loss of the productive capacity of the soil, due to reduced soil fertility and increased soil erosion, with these problems being mutually related. This result corroborates those obtained by Tsufac et al. (2021), who concluded that agroforestry systems with different practices improved soil fertility, leading the authors to recommend the use of agroforestry in some activities or as part of productive farms.

Among the biophysical parameters analyzed by Cooper et al. (1996) in their review, they found that declining soil fertility was a serious problem for farmers and that hedgerow intercropping systems somewhat reduced this effect. Farmers in a humid tropical region reported a relationship between certain tree species used in the agricultural systems and increased soil fertility. In relation to soil erosion, Cooper et al. identified problems due to the use of sloping areas for crops and how agroforestry could be applied for soil conservation in these conditions.

Regarding biological diversity Garrity (2004) identified ways in which the adoption of agroforestry systems is beneficial, the first is that "intensification of agroforestry systems can reduce exploitation of nearby or even distant protected areas." As identified by Murniati et al., 2001, Garrity et al., 2003, and Garrity (Garrity, 2004) the "expansion of agroforestry systems can increase biodiversity in working landscapes."

The implementation of agroforestry increases the species and within-species diversity of trees in the farming systems. To summarize, there are positive findings on the use of agroforestry systems for the conservation of natural systems, and adoption of these systems can reduce the need to expand into new areas for agriculture production because previously used land is degraded by erosion and production diminishes due to loss of natural soil fertility.

Agroforestry has been adopted by farmers to restore soil quality, as evidenced by Franzel (1999), with practices such as improved fallow systems in different parts of Africa, which were found to increase the availability of nutrients for the crops. This improved fallowing proved to be an efficient strategy for low-income families. However, Franzel emphasizes the need to investigate why other farms have not adopted this practice and why they have not been recommended by the public sector. According to (Feliciano et al., 2018), there is substantial evidence that improved fallowing increases above-ground carbon sequestration, and together with agroforestry helps to retain carbon in the soil. However, previous studies had inconsistent methodologies and few quantitative analyses and were thus unable to support implementation schemes for farmers and communities.

This study found that low soil fertility is a frequently cited problem and the search for productive systems capable of adapting or mitigating this limitation can help farmers in the regions analyzed. Furthermore, as Nuberg (1998) found in Australia, where the fertility of the soil is low due to intense wind erosion, the use of windbreaks for erosion control improved both problems, although the authors point out that more research is needed on the arboreal species used in these corridors. These efforts were also found in Brazil’s Cerrado region, in a study by Miccolis et al. (2019), and the authors concluded that agroforestry promotes soil restoration with non-accounted soil functions and benefits to the environment.

One of the most beneficial factors tree species offer to soil fertility is an increase in living and dead plant biomass. Some studies conclude that the presence of litter prevents the loss of nutrients from erosion due to the direct impact of rainfall on the soil, as verified by Penereiro et al., 2002, Costa et al. (2013) and by Zomer et al. (2016) in different climatic conditions. De Souza et al. (2020) indicated that the management of an agroforestry system with pruning and disposal of green biomass in the soil promotes the recovery of soil chemical fertility faster than natural regeneration. A study on a cocoa farm showed that to improve the decomposition and absorption of nutrients, the enrichment of the ground cover material with biomass from gliricidia trees resulted in a faster rate of decomposition than the use of just cocoa (Kaba et al., 2021). This indicates that there is a need for further studies about which species should be part of an agroforestry arrangement according to the environmental characteristics. However, another study by Cardinael et al. (2018) found no significant difference in carbon stock in the presence of a biodiverse land cover, when compared to an 18-year-old agroforestry system and the control plot. In the same study, it was not clear if the increase in the number of tree species favored an increased stock of organic matter over time.

Thus, in the short term, we can infer that there is a perception of qualitative improvement from the adoption of agroforestry, at least in superficial soil layers; however, this benefit has not been proven in quantitative terms. Nevertheless, Cardinael et al. (2015), Cardinael et al. (2017), Cardinael et al. (2018) showed that there was an increase in soil organic matter in an agroforestry system from the larger amount of biomass added to the system. In agreement with the results found in this study, the increase in fertility perceived by farmers and mentioned in the studies analyzed may be related to an increase in soil organic material in agroforestry systems.

Several studies have identified soil erosion as a critical factor in food production and the conservation of arable land. In a simplified view of agroforestry potential by (Cooper et al., 1996), erosion by water and wind can be reduced with the use of tree species. However, there has been intense debate about the interactions between different species and their root systems. This was analyzed by Schroth (1999) in a review of underground interactions in agroforestry systems, which showed that the development and evolution of plants, in general, have always been associated with competition for space, light, soil, and water resources, and the interactions are not always negative. According to Schroth (1999), some species complement each other or even facilitate a better environment for plant growth, and this can be enhanced with proper management and research on the interactions of different species and their root systems, especially those used in agroforestry. According to Cardinael et al. (2018), a linear model was not efficient for determining the positive or negative interactions between the deeper roots; however, an increase in the availability of organic matter stock between the tree rows was found.

The various studies analyzed here show that the use of tree species brings a differential to agriculture production, but as mentioned by Luedeling et al. (2016), it is important to develop larger and more reliable databases with information on tree performance, for a wide range of agroforestry systems and in different environmental conditions and soil types. The methodology used in this study identified the potential for improving soil conditions, in terms of erosion and fertility, offered by the adoption of agroforestry, highlighting studies that indicate that the use of an agricultural system that integrates crops and tree species can mitigate a widely discussed problem, the loss of soil productive capacity due to decreased soil fertility (Hartemink et al., 2008).

There is, however, evidence that the perception of improved soil quality is not always confirmed by quantitative measures of soil fertility, according to recent studies. Integrated studies may be a new approach to expand research on agroforestry systems in Brazil, where the adoption of agroforestry is associated with the agronomic, socioeconomic, and climatic conditions of the micro-region in which it is applied (Schembergue et al., 2017). This adoption must be accompanied by detailed knowledge of the soil and spatial interactions. According to Schroth (1999), these interactions must be predicted and optimized through proper selection and management of species, and it is already possible to predict quantitative evidence of their benefits with mathematical models (Cardinael et al., 2018).

CONCLUSION

The analysis of secondary sources about the adoption of agroforestry to achieve sustainable food production and reduce land degradation shows that agroforestry can improve soil fertility and reduce wind or water erosion. Agroforestry proved to be important for improving soil quality in several aspects, making this agricultural production system an ally in achieving the MDGs. This analysis found that it is widely recognized that agroforestry qualitatively increases soil fertility and reduces the impact of soil erosion in different regions, but quantitative studies of these benefits are needed since some research has concluded that there are no significant benefits in terms of increased soil organic matter, which is a major indicator of soil fertility.

The volume of sites and research about the use of agroforestry to improve and conserve soil in the tropics may be related to the predominantly low natural fertility of the more weathered soils most common in these regions. Yet, the greater speed in nutrient cycling and plant biomass growth in sub-humid and humid climates facilitates the use of agroforestry systems to mitigate problems of nutrient availability inherent to tropical soils. There is evidence from studies that prove the increase and speed of nutrient cycling from the presence of different species in the same plot, although more studies are needed to be able to widely recommend agroforestry in different regions. The analysis of the different studies allows us to conclude that agroforestry is a safe path to sustainable agricultural production and there was no evidence to the contrary, that is, no study has pointed to a loss or reduction of ecological benefits to the soil.

Regarding the information and knowledge compiled about the benefits of agroforestry, more information is needed on the adoption of these systems in different locations, soils, and climates, which can have great importance to the implementation of policies designed to control soil erosion and increase soil fertility, thereby reducing land degradation. The evaluation of the economic, environmental, and social benefits of increasing soil fertility and decreasing erosion offered by agroforestry systems, under different conditions, is necessary to support public policies aimed at the use of agroforestry as a sustainable agricultural practice. In this sense, we emphasize the need for local studies that point to qualitative improvements and quantitative increments in the arrangements between species for different purposes according to the environment and the needs of farmers.

AUTHOR CONTRIBUTIONS

MM: Conceptualization, search for secondary sources, methodology, writing—original draft, review and editing, visualization. LA: Supervision, review and editing, funding acquisition. AD: Review. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Quantification of Gypsum in Soils: Methodological Proposal

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Gypsum is widely found in soils under arid and semi-arid climates due to its semi-soluble nature. In spite of that, they are less known than other soils, and this has generated some misunderstandings in some initial pedological concepts and in soil classification systems. In addition, the quantification of gypsum, and in particular of its secondary accumulations is affected by the sampling procedures and sample handling in the lab; besides by the methods used for the determination of gypsum themselves, since they differ on the accuracy, cost, and expertise needed. The objective of our research is to improve some laboratory procedures in order to determine and quantify gypsum in the soil, especially secondary accumulations. We applied several methods of sample handling and gypsum analysis to a loess profile in the Ebro Valley (NE Iberia), consisting of 10 horizons containing gypsum in varying amounts (0 to about 50%); of different sizes and morphologies. We propose a protocol considering procedures (sieving or not), qualitative determinations and two methods (turbidimetry and dehydration of crystallization water) for an optimal determination of gypsum depending on the characteristics of the sample and compared them with the acetone method (US Salinity Laboratory Staff, Agric. Handb., 1954, 60, 175; Nelson, 1978, 181), as it is the reference method in the main Classification Systems. The results obtained after applying the different methods for the analysis of gypsum in bulk samples have allowed us to propose a decision tree procedure for the determination of gypsum in soil materials. This procedure includes, determination of gypsum in all fractions, coarse and fine, the estimated amount of gypsum in the field (as a major or minor component) and the presence of other components that may interfere with the results. The most accurate results are obtained with those methods based on the loss of gypsum water upon heating when gypsum content is >4%, and with the turbidimetric method in case of lower amounts of gypsum. Finally, we discuss the implications of these analyses when a soil is classified according to the main soil classification systems (WRB 2014; Soil Survey Staff, SSS- NRCS, 2014).

Keywords: soil classification, gypsum, secondary accumulations, loss of water crystallization, turbidimetry, analytical protocol

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INTRODUCTION

In comparison with other types of soils, those containing gypsum have not been widely studied. Due to its semi-soluble nature they are mainly found in arid and semi-arid areas of the world (FAO 1990), which have been traditionally less surveyed than, e.g., other soils in temperate areas. This lack of research created misunderstandings in some initial pedological concepts. For instance, in the past, gypsum soils were classified either as saline or as calcareous soils (as in the 7th approximation of Soil Taxonomy, Soil Survey Staff, 1990).

The Soil Map of the World (FAO 1988) defines "gypsiferous soil material" as that containing at least 5% gypsum. Herrero et al. (2009) distinguish gypsiferous from gypseous soils on the basis of gypsum content: the first term would be applied when gypsum content is small and the main soil properties are not controlled by it, and the second to soils in which gypsum is the major component (reaching 90% or more). In other cases, gypsiferous soils have been defined according to land use, as those containing a sufficient amount of gypsum to interfere with plant growth (FAO 1990). Casby-Horton et al. (2015) indicate that gypsum contents higher than 30% have strong implications for physical and chemical properties relevant for agronomic purposes.

Numerous authors (Eswaran et al., 1981; Ilaiwi, 1983; Herrero et al., 1987; Herrero and Port, 1991; Herrero et al., 1992) have contributed over the years to the improvement of the knowledge of soils with gypsum. Due to its relatively high solubility (2.4 g L-1 at 25°C) gypsum is seldom found as inherited from the parent material in arid and semiarid soils but as secondary gypsum accumulations after several dissolution/reprecipitation cycles. The main morphological types of gypsum accumulations as described in the literature are presented in **Supplementary Table S1**.

Some of these accumulations are cemented, either completely or partly. This is due to the growth of loose gypsum crystals within a confined pore space until they join together forming a xenotopic fabric as seen in thin section (Poch et al., 2018). The concept of cementation has been misused in literature, due to the fact that many gypseous materials become very hard when dry, but disintegrate when submerged in water or become friable when wet (Watson 1985; Porta and Herrero 1988), as it happens with some gypsum "crusts" or "encroûttements" (**Supplementary Table S1**). Another possible explanation for this confusion may be the presence of cements other than gypsum (Dekkiche, 1974; Kulkc, 1974). However, this origin seems unlikely since it has been experimentally demonstrated that when these cements are eliminated, the material does not lose cohesion, and also, as Halitim (1985) indicates, a high gypsum content makes the behavior of a minority compound impossible as cement.

Current methodologies for describing and defining soils in the two main classification systems "Soil Taxonomy" (S.S.S. 2014) and "World Reference Base for Soil Resource" (WRB 2014–2015) are not very precise when applied to gypsum soils, since they do not they take into account all the characteristics related to their composition, genesis and behavior. In addition, the basic requirements are ambiguous when describing them in the field (definitions of Gypsic and Petrogypsic horizons are intertwined when they should be defined individually), and other criteria are difficult to observe, require additional chemical analysis, and are very difficult to determine (Herrero ey al, 2004).

Another limitation when applying the classification systems is related to the definitions of diagnostic horizons and materials. For instance, both classifications include the Gypsic horizon as a diagnostic horizon, but the definitions are not identical. In both systems a minimum of 5% gypsum (by weight) is required in the fine Earth, but depending on the diagnostic feature or horizon, other gypsum contents or estimates of volume percentages are required, whose precision is not very high. Several qualifiers are used in these systems for gypsum soils. Soil Taxonomy (SSS-NRCS 2014) defines the terms Gypsic, Gypsifactic, and Gypseous while the WRB (2014–15) includes the qualifiers Gypsiric, Artzic, Gypsifractic, and Hypogypsic. The qualifier Hypergypsic is also defined differently in both systems: the fine Earth must contain a minimum of 40% gypsum in Soil Survey Staff, 2014), and 50% gypsum in the World Reference Base (2014–15). These differences can lead to misunderstandings and make the use of the classifications difficult.

The determination of gypsum content in soils is affected on the one hand, by the management of the sample prior to the analysis, and on the other hand, by the analytical methods themselves.

A qualitative test to detect the presence of sulphates using a $BaCl_2$ solution can be used in the field (Porta and López-Acevedo 2005). This test is especially useful when trying to distinguish calcium carbonate from gypsum when it is found as small crystals, as both of them are white.

The standard procedures in soil science laboratories comprise a preliminary sieving to obtain the fine Earth (mineral particles less than 2 mm), before carrying out many of the analyses. Soils with gypsum often contain accumulations of gypsum (either hard or discontinuously cemented) larger than 2 mm, that will not pass through the sieve and therefore will not be included in the sample, which can lead to an erroneous estimate of the actual amount of gypsum. Moreover, the gypsum-containing coarse elements are often fragile and therefore will vary depending on the intensity of the grinding and sieving treatment.

There are several methods to determine the gypsum content in the soil, although not all are equally accurate. In addition, the costs and the time required vary remarkably among them.

The acetone method is the reference wet chemical method for gypsum analysis (US Salinity Laboratory Staff, 1954). It is based on the complete dissolution of the gypsum in the sample, followed by its reprecipitation by adding acetone. The precipitate must be further completely dissolved again and sulphates measured in the solution. There are several ways to quantify gypsum when applying this method: either measuring the electrical conductivity (EC), using a correlation between EC and dissolved salts (US Salinity Laboratory Staff, 1954); or analyzing either SO_4^{2-} (Loeppert and Suarez 1996) or Ca^{2+} (Van Reeuwijk 1987) ions. Some of the methods based on the determination of SO_4^{2-} ions are very precise and can even determine very small amounts of sulphates, on the order of micrograms (Horton and Thomason 1951), but they are time consuming and are difficult to apply. Furthermore, the results may be erroneous when other sulphate minerals are present, since acetone can react with them, as well as with anhydrite (Soil Survey Staff 2014). In these cases, corrections are necessary due to exchange error (reactivity with other sulphates that do not come from gypsum) and occlusion effects of acetone (Lagerwerff et al., 1965). On the other hand, the methods based on the measurement of the EC present the same limitations as the previous method and, in addition, they consume a lot of time, since they require the complete dissolution of the gypsum, a very slow step due to the slow kinetic dissolution of the gypsum (Hirst and Greaves 1922; Lagerwerff et al., 1965). Therefore, it is not a very suitable method for gypsum-rich samples, which require very large amounts of water.

Thermogravimetric methods, based on the loss of crystallization water at low temperatures, allow a faster determination, although they require a minimum amount of gypsum (about 4%) in the sample, to be able to measure it with enough accuracy (Nelson et al., 1978; Lebron et al., 2009). The differential water loss method (Artieda et al., 2006) is based in the same principle. It estimates the amount of gypsum water that is lost when the sample is heated at different fixed temperatures (normally 70–90°C), with an accuracy of approximately 2% gypsum (Artieda et al., 2006). Another method, also based on the water loss when the sample is heated in a temperature range of 70°C to 135–150°C, is OMRAN GypSim method (Omram, 2016) which allows to determine the gypsum content within 1% accuracy by heating the sample to 150°C (temperature at which gypsum becomes anhydrite). Other non-destructive methods based on loss of mass due to the release of water from gypsum use X-ray fluorescence (XRF) (Weindorf et al., 2013) and reflectance; and when combined, the precision increases considerably (Herrero et al., 2020). However, these methods are more expensive and are not easily accessible.

Gypsum rocks are frequent in the Ebro valley (NE Iberia), which have their origin in a Miocene evaporitic basin. This parent material is the origin of the generalized occurrence of soils with varying contents, sizes and degrees of cementation of gypsum (Poch et al., 2021), which poses problems of analysis and classification.

The objectives of this research are to establish the best approaches to characterize gypsum concentrations in soils, taking into account the forms, sizes and amounts of gypsum, and using different methods in order to make recommendations of sample handling and gypsum analysis for genesis and classification purposes.

MATERIALS AND METHODS

Field Description, Sample Handling and Physical-Chemical Analysis

The profile chosen to develop this methodology is Mas de Caspolí (Mequinenza, Zaragoza, coordinates UTM: X: 265134; Y: 4,580,885) located in the upper section of a slope (>3%), at an altitude of 375 m asl and with a depth of 5.5 m. The profile was described in the field following CBDSA, 1983) and sampled for mineralogical, chemical and physical analyses. The samples were taken in bags and air-dried in the lab at room temperature.

Between 300 and 500 g of the air-dried samples were manually sieved to separate the fine Earth (less than 2 mm) from the coarse particles (larger than 2 mm), in order to preserve the gypsum accumulations (nodules, crystals and gypsum intergrowths) observed in the field (**Figure 1**). As a result, three subsamples were obtained from each horizon for subsequent gypsum content determination: fine Earth (<2 mm), coarse elements (>2 mm) and the unsieved sample (total fraction). All samples and subsamples were weighed before and after sieving (**Figure 1**). All fractions were crushed in an agate mortar before analysis.

Routine physico-chemical analyzes as described by Porta, 1986) were carried out on the fine Earth fraction. Calcium carbonate equivalent ($CaCO_3$ eq.) was determined by gasometry with the Bernard´s Calcimeter. The organic carbon (OC) was obtained by wet oxidation following Walkley-Black method. pH was measured with a pH-meter in a 1:2.5 soil:water suspension and the electrical conductivity ($EC_{1:5}$) with a conductimeter in a 1:5 soil:water extract.

The mineralogy of the clay fraction (both coarse and fine clay) was determined through XR diffraction using a Bruker model D8 Advance powder diffractometer at the Facultad de Geología of the Universidad Complutense de Madrid. This equipment has a Cu-anode and a SOL-X energy dispersion detector. The diffractometer works with Bragg-Brentano measurements. The software used for the acquisition, treatment and evaluation of diffractometric data was DIFFRACplus. The preparation of the clay mineral samples included treatments to remove carbonates, organic matter and sulphates using the acetic acid attack method (Porta, 1998). After separating the clays and the preparation of oriented aggregates, a dry air (NT), a solvation with ethylene glycol and a heat treatment at 550°C were performed before reflection analysis in the 060 plane.

Analyses and Morphoscopy of the Coarse Fraction

Some representative gypsum crystals and intergrowths from the coarse fraction were carefully cleaned with a brush and a small chisel prior to their observation and description with the help of a binocular microscope (OLYMPUS-SZX16, objective: SD PLAPO 1XPF). Their colors, cleavage, crystalline habit and type of crystal aggregation were described, as well as other properties that could help to understand their genesis.

Gypsum Analysis Methods

Qualitative and Prospective Tests

The presence of sulphates can be detected in the field by the formation of a precipitate after adding a drop of $BaCl_2$ 10% to a soil:water suspension and subsequent filtration (Porta & López-Acevedo 2005). It indicates the presence of gypsum, as well as of other sulphates in salt-affected soils (as mirabilite, burkeite, bloedite or jarosite). In the lab a 1:5 soil:water suspension (volume ratio) was used (Porta & López-Acevedo 2005). This test cannot detect gypsum concentrations below 0.26% (Porta et al., 1986).

The electrical conductivity of a 1:5 suspension ($EC_{1:5}$) also indicates the presence of gypsum, since the EC of a solution saturated with gypsum is 2.2 dS/m at 25°C. This value remains fairly constant when analyzing gypsum-containing soils regardless of the soil:water ratio, due to the relatively low solubility of gypsum (2.4 g L^{-1}at 25°C) that saturates any solution very fast in absence of other salts.

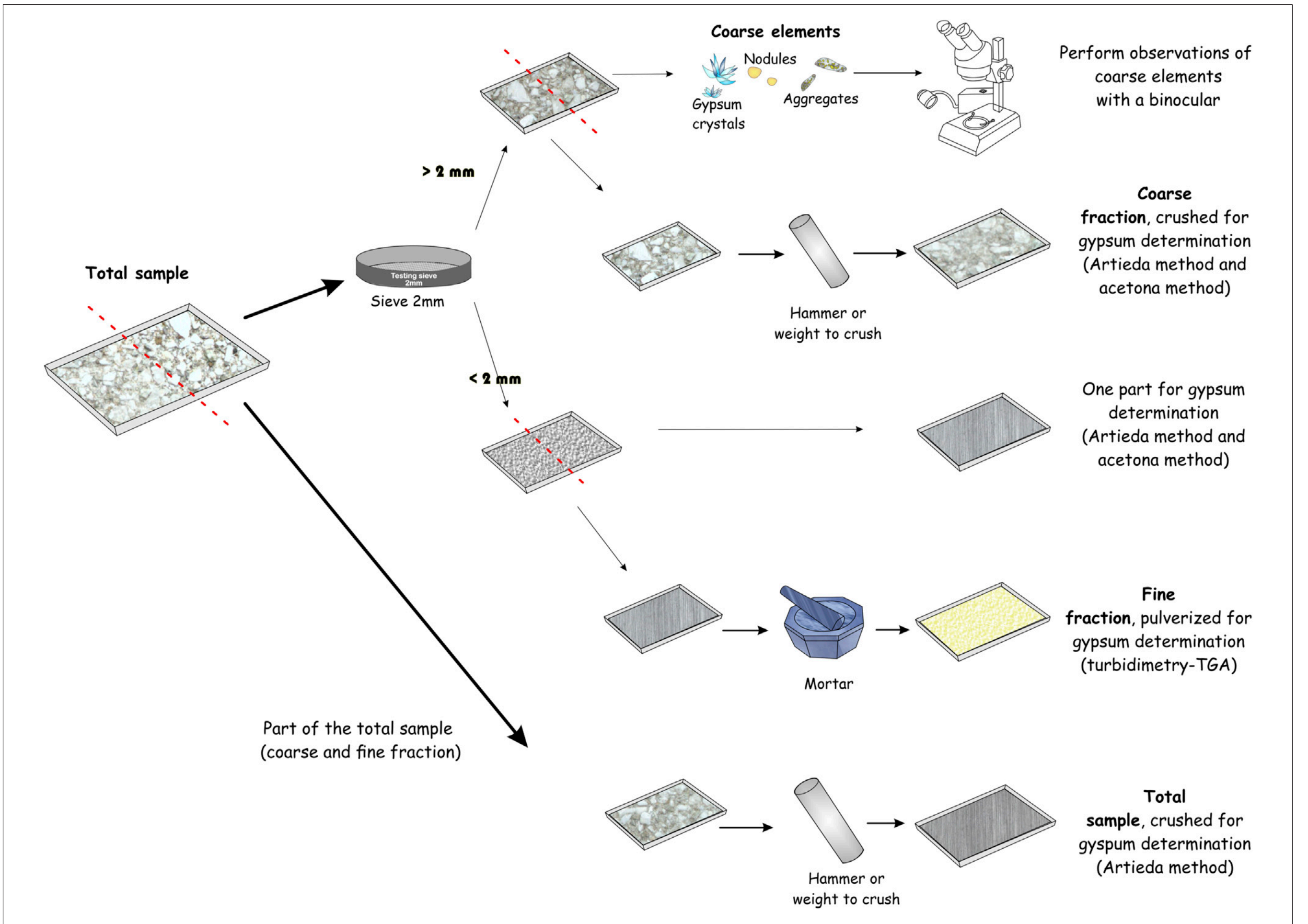

FIGURE 1 | Scheme of the protocol followed to prepare the samples.

Artieda Method

This method measures the difference in weight resulting from the loss of crystalline water from the gypsum molecule, when the sample is heated to fixed temperatures, which determines the transformation of gypsum into bassanite and anhydrite. Since not all the water is lost when the sample is heated, it is necessary to apply a recovery factor (Burns et al., 2002).

We used the method proposed by Artieda (1993), the refined method proposed by these authors (Artieda et al., 2006), and the method proposed by Lebron et al. (2009) following the recommendations of Herrero et al. (2020).

The steps followed have been the same as those proposed by Artieda et al. (2006), applying the following intervals (40–105°C; 70–105°C):

(1) Weigh about 15 g of the air dried sample,
(2) Place it on an oven container in a hot air oven at 40°C for 48 h,
(3) Let the sample cool down in a desiccator to prevent it from absorbing moisture,
(4) Weigh the sample again,
(5) Place it again into the oven, at 70°C, for further 48 h,
(6) Leave the sample again in a desiccator and weigh it again once cooled.
(7) Repeat the process (steps 5–6), now at 105°C.
(8) Calculate the amount of gypsum in the sample, applying the following expression:

$$Gypsum\,\% = \left(\frac{(ws - wf)}{(ws - wc)}\right) \times 100\left(\frac{100}{rf}\right)$$

ws: sample weight at the initial temperature (40°C or 70°C); *wf*: sample weight at the final temperature (105°C); *wc*: container weight; *rf*: recovery factor according to the temperature interval.

The recovery factor is 19.1% when the interval between 70 and 105°C is used (Artieda et al., 2006), and 19.39% for the interval 40–105°C (Artieda 1993).

This method loses accuracy when gypsum contents are lower than 8% for the temperature ranges 40–105°C (Artieda et al., 2006). Furthermore, it is not recommended for gypsum contents lower than 2% when calculated for temperatures higher than 70°C (Artieda et al., 2006). Moreover, previous experiences in our lab (unpublished) seem to indicate that the precision is already lower when there is less than 5% gypsum.

Three replications were carried out for each sample and the standard deviation was calculated, in order to quantify the variation between the gypsum results obtained, in the different fractions (total, coarse and fine).

Finally, to determine the precision of the method, three replications have been carried out for each fraction of the Artieda method, in the two temperature ranges indicated (40–105°C; 70–105°C).

The results obtained from the replications have been assessed by taking into account the weight of each sample fraction (fine and coarse), to obtain the total gypsum content in each horizon, and compare them with the one obtained in the total sample. The expression used to calculate the total gypsum content is as follows:

$$\%\,\boldsymbol{Total\,gypsum} = \frac{(\%\,\boldsymbol{A\,x\,weight\,FF}) + (\%\,\boldsymbol{B\,x\,weight\,CF})}{\boldsymbol{weight\,TF}}$$

%*A*: % gypsum in the fine fraction; weight FF: grams of fine fraction; %*B*: % gypsum in the coarse fraction (contribution of the coarse fraction to total gypsum (B)); weight CF: grams of coarse fraction; weight TF: grams of total fraction.

Turbidimetry Method

Gypsum content can be determined by turbidimetry in absence of other sulphates (Porta et al., 1986). This method is based on the precipitation of $BaSO_4$ and other sulphate salts after the addition of Ba^{2+} (as $BaCl_2$) in a sulphate-containing solution, and the estimation of the turbidity of the resulting solution by spectrometry. All gypsum in the sample must be dissolved before the addition of $BaCl_2$, and therefore it is necessary to have a prior rough estimate of the gypsum content, since it will affect the dilution factor, which varies between 1:50 to 1:1000 (soil: water) for gypsum contents between 5 and 90% respectively (Porta et al., 1986). It is also necessary that the precipitate remains in suspension during the measurement with the spectrometer, and that gypsum standards are prepared and measured to obtain a calibration curve. This technique seems to give better results when analyzing non-saline samples with low gypsum contents (<5%).

The detailed turbidimetry method procedure is as follows:

(1) Weigh the required pulverized sample quantity to prepare a 250 ml of solution by adding deionized water, and stir for 8 h on a shaker.
(2) Put 200 ml of the extract in 250 ml-centrifuge bottles, and centrifuge at 8,000 rpm for 10 min (In this study, a Beckman Coulter centrifuge, model Allegra 25 R was used).
(3) In 50 ml flasks, add in the following order: the amount of extract required (ml) (It is advisable to previously shake the prepared extract to homogenize it), deionized water, 10 ml of stabilizer solution (135 g of $CaCl_2{\cdot}2H_2O$+ 50 ml of concentrated HCl +500 ml ethylene glycol in 1 L of solution), deionized water, 0.2 g of $BaCl_2{\cdot}2H_2O$ powder and deionized water up to 50 ml.
(4) In addition, five standards of 0, 10, 20, 30, 40 ppm of SO_4^{2-} are prepared with 0, 0.5, 1, 2, 3 ml, respectively, of a solution of SO_4^{2-}-1000 ppm.
(5) Allow the reagents to act for 8 min. After this time, the readings must be carried out in the next 15 min. Due to this time constraint, it is important to choose an adequate number of samples in each run to allow time to read.
(6) Read the turbidity with a spectrophotometer at 420 nm (we used a Unicamp UV-VIS ultraviolet spectrometer, model 9423).

Thermogravimetry Method

The Thermogravimetric Analysis (TGA) consists in the continuous measurement of the mass of a substance, which is monitored as a function of temperature (T) or time (t), since the sample specimen is subjected to a constant temperature increase (T/t) in a controlled atmosphere. Its application to gypsum determination is based on the loss of crystallization water of gypsum molecules at certain temperature ranges. This technique has been successfully used in gypsum analysis (Al-Muktar, 1987; Poch 1992). It was applied to the samples of the 2Cy1 and 4Bym horizons of profile Mas de Caspolí, in order to compare the results obtained with those from the other analyses.

The equipment used was an SDT Q600 V8.3 Build 10.1 Thermogravimetry with ±2% precision, which allows simultaneous measurements of weight change due to heating (TGA) and differential heat flow (DSC). The measurements were carried out on approximately 10 mg of sample, therefore a thorough homogenization of the sample -mixing with a spatula- was required prior to weighing. The temperature range applied was from room temperature (aprox. 25°C) to 1000°C with an increase of 10°C/min and with an air flow system of 100 ml/min.

Acetone Method

The Acetone method is a wet chemical method based on the measurement of the electrical conductivity of the solution resulting from the dissolution of the gypsum in the sample and its subsequent reprecipitation by adding pure acetone (99%). This method has been applied to all the sample fractions (coarse and fine fraction) which has allowed estimating the amount of real gypsum in each fraction.

The analysis protocol followed has consisted of the following steps, based on the protocol proposed by the US Salinity Laboratory Staff. (1954).

(1) Weighing of the soil sample between 2–20 g (the amount will depend on the EC of the previously measured sample, taking >850 dS/m as the limit).
(2) Dissolution of the samples with 100 ml of milliQ water, shaking the sample for 30 min and subsequent filtering (Millipore filter, 185 mm, Whatman No.2V).
(3) Addition of 5 ml of pure acetone (99%), mix manually and allow to flocculate
(4) Centrifuge without stopper, at 5,000 rpm for 5 min (Centrifuge: Beckman Coulter/Allegra 25R)

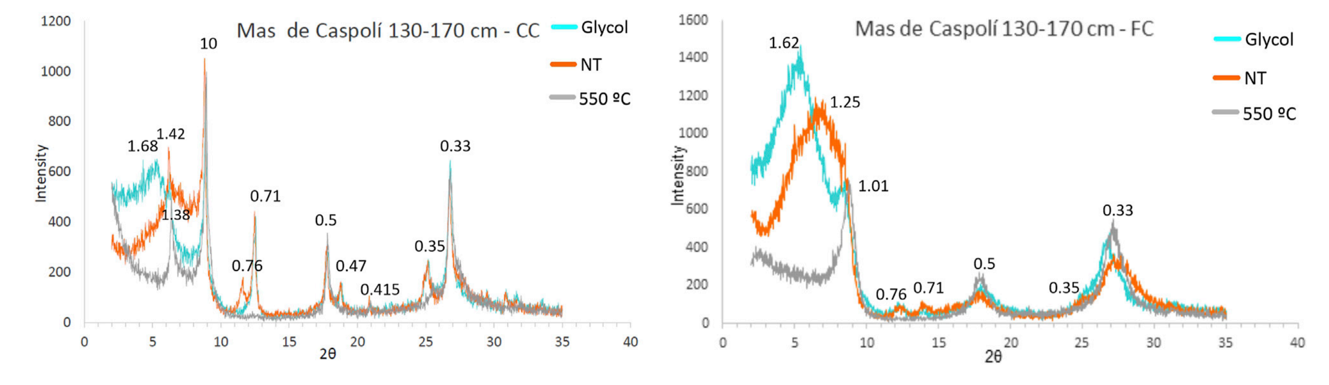

FIGURE 2 | Diffractograms of Coarse Clays (CC) and Fine Clays (FC) of the 3Bwy1 horizon (130–170 cm). The three lines correspond to the three treatments used (Glycol, dry air (NT) and 550°C). Peak values (nm) observed to identify clay mineralogy are indicated.

(5) Decant the remainder and add a further 5 ml of acetone. Mix with a laboratory Vortex mixer for approximately 20 s
(6) The centrifugation is repeated at 5,000 rpm for 5 min, to re-precipitate the gypsum and the remaining acetone is decanted.
(7) Finally, add 10 ml of miliQ water and mix the samples in a laboratory Vortex mixer for 20 s
(8) Reading of the electrical conductivity in a conductivity meter (Crison GLP31) and the pertinent calculations are made to obtain the % of real gypsum, following the equations proposed by the US Salinity Laboratory Staff. (1954).

RESULTS

Profile Description and Analyses

The studied profile has been developed on loess, deposited over the underlying material (below 5.5 m) consisting of Miocene shales, limestones, calcareous sandstones and gypsum. It has been classified as a Typic Haploxerept (Soil Survey Staff, 2014). It contains several types of gypsum accumulations which generate crystals of different sizes and morphologies. **Supplementary Table S2**, shows a summary of its field description and its main chemical properties.

The results of clay mineralogy analysis, through X-ray diffraction (**Figure 2**), have given peaks that correspond to interstratified illite-montmorillonite (peaks >1–1.4 nm, in air dry, 1.6–1.8 nm with glycol and decay to 1 nm at 550°C), illite (very sharp peak at 1 nm), kaolinite (peaks at 1.25, 0.43 and 0.33 nm), quartz (very sharp peaks at 0.43 and 0.33 nm, especially in the coarse fraction) and chlorite (peaks at 1.4, 0.76, 0.47, 0.35 nm).

Partition of Fine Earth/Coarse Fractions

The different fractions obtained from the sieving have been subdivided into three representative parts, trying to make an equal division that would represent a similar percentage of each fraction.

The fine Earth includes 61%–83% of the mass of the sample, with a relatively small deviation among the replicates measured. The **Supplementary Table S3**, shows the partition, as a percentage by weight of each fraction, coarse fine, and total sample, of the manually sieved profile horizons. The upper horizons do not appear because they consisted only of fine Earth.

Morphoscopy of the Coarse Gypsum Fragments

The observation and description of the morphologies of the secondary gypsum accumulations has made it possible to know which morphologies are the most abundant and thus help to understand their formation (**Table 1**). Some of the accumulations observed are presented in **Figure 3**, with the aim of showing the range of sizes and the variability of morphologies that can be found.

Observing the accumulations with binocular reinforces the information described in the field. The horizons with vermiform gypsum and gypsum coatings (2Cy1, 3Bwy, 4Bky2) present crystals with too small sizes (<200 μm) to observe them in detail. The coarse fragments of horizons with larger accumulations, such as gypsum rhizocretions, crusts or hard nodules (3Cy2, 5Bym) can be better observed with binocular because they reach larger sizes, which allow a detailed description of the morphologies, growths and orientations.

Determination of Gypsum Content

Qualitative Tests

The results obtained with the qualitative test of $BaCl_2$ give a first indication of the horizons that may contain gypsum. This test has a lower limit of 0.26% (Porta et al., 1986), detecting very small amounts of gypsum. However, it is not a definitive test, since it gives positive results in soils with a very low amount of gypsum, probably due to the presence of other soluble salts or sulphates.

This case is exemplified in the BC horizon, in which no gypsum has been described in the field and the $EC_{1:5}$ value is very low. The most likely explanation is that there may be a very

TABLE 1 | Morphology of the coarse fraction observed with the binocular.

Horizon	Crystal morphologies	Growth/twinning/orientation	Colour and sizes
2Cy1	Pseudocubic crystals, with one axis more developed	Aggregates without preferential orientation and random arrangement. Some fragments are originally infillings of biopores (vermiform gypsum). In this case, crystals have certain radial orientation. Many of the crystals are coated by micritic groundmass, which masks their identification	Transparent-dirty and slightly yellow. The smallest crystals have sizes between 30–50 μm
3Bwy1	Mostly lenticular and prismatic crystals, with a good development of the long axis, giving them lenticular shapes with flat faces	Aggregates with a random arrangement, sometimes the lenticular crystals appear to form small desert roses. The large crystals show regrowths of small crystals on their faces, perpendicular to them. Many of the crystals are coated by micrite, which masks their identification	Transparent-dirty. Crystals sizes from 50 to 200–300 μm
3Cy2	Crystals with different morphologies: flat prismatic, lenticular and small fibrous	Arrangement in aggregates without a clear preferential orientation, some fragments as massive aggregates. The large crystals show regrowths of small crystals on their faces, perpendicular to them	Transparent. Crystals sizes ranges from very large crystals (0.2–0.4 mm) to small crystals (<50 μm)
		Many crystals covered with micritic groundmass but some idiomorphic crystals have clean faces and higher luster	In some pore fillings, the size of the crystals decreases towards the center
4Bwy	Crystals, Flat-prismatic and subangular prismatic with rounded edges	Random aggregates with no specific orientation. The smallest crystals grow in favor of the flat faces of the large crystals	Transparent to yellowish, dirty
	Lenticular crystals, some sub-rounded with less developed long axis	On some faces of lenticular crystals, cleavage lines appear parallel to the long axis Small desert roses made of lenticular crystals	Crystal sizes range from microcrystalline, <50 μm, up to large, approximately 200–300 μm long
4Bky2	Prismatic and acicular microcrystalline crystals	Random distribution	Whitish. Microcrystalline (<50 μm) sizes
5Bym	Very well developed individual and twinned lenticular crystals. Acicular microcrystals	Aggregates predominate, as well-formed desert roses whit a very good crystalline development. These formations allow a very good observation of crystals shapes	Grey-yellow
		On some faces of lenticular crystals, cleavage lines appear parallel to the long axis	Crystals sizes range from <50 μm to large crystals of several mm

small amount of unobservable sulphate in the matrix, that makes the test positive.

Measuring the electrical conductivity (1:5 extract) helps to better specify the possibility of the detection of gypsum. The horizons with visible gypsum in the field are positive in the qualitative test and yield $EC_{1:5}$ < values over 1 dS/m, and between 2.3 and 2.6 dS/m in the four central horizons. Likewise, horizons with conductivities higher than 1.3 dS/m, despite having a low amount of gypsum, show that this amount is already sufficient to raise their electrical conductivity above 0.35 dS/m, the limit to be considered slightly saline (Porta & López-Acevedo 2005).

Table 2 contains the results of the qualitative test for sulphates using BaCl2, and the value of EC in the 1:5 filtered extract that can serve as indicator of the presence of gypsum.

Gypsum Quantification

The results obtained with the different methods (Artieda 40–105°C; Artieda 70–105°C; turbidimetry and thermogravimetry) are shown in **Tables 3**, **4**. **Figure 4** is the thermogravimetric diagram obtained from the analyzed 5Bym horizon. The green lines (weight loss (%)) and blue lines (peaks at which weight loss occurs, as a derivative of weight *versus* temperature (%/°C)) are related to the variation in sample weight at temperature rise. The pink line (heat flow (W/g)) and brown line (sample temperature difference (°C/mg)) are related to the temperature variation during the analysis. Finally, the peaks of gypsum and carbonate loss have been marked with vertical red lines.

In general, most of the results obtained with Artieda 40–105°C give the highest values, while the results obtained with turbidimetry and thermogravimetry give lower values and reach higher precision for low amounts of gypsum. The acetone method, however, clearly underestimates gypsum, especially in the gypsum-richest samples, without exceeding 15% gypsum with this method, in any of the analysed fractions.

In addition, the standard deviation obtained with the Artieda method in both temperature ranges is relatively low, except for the 2Cy1 horizon, which presents a higher value in the result obtained in the total sample, probably due to a low representativeness of the sample, as will be discussed later.

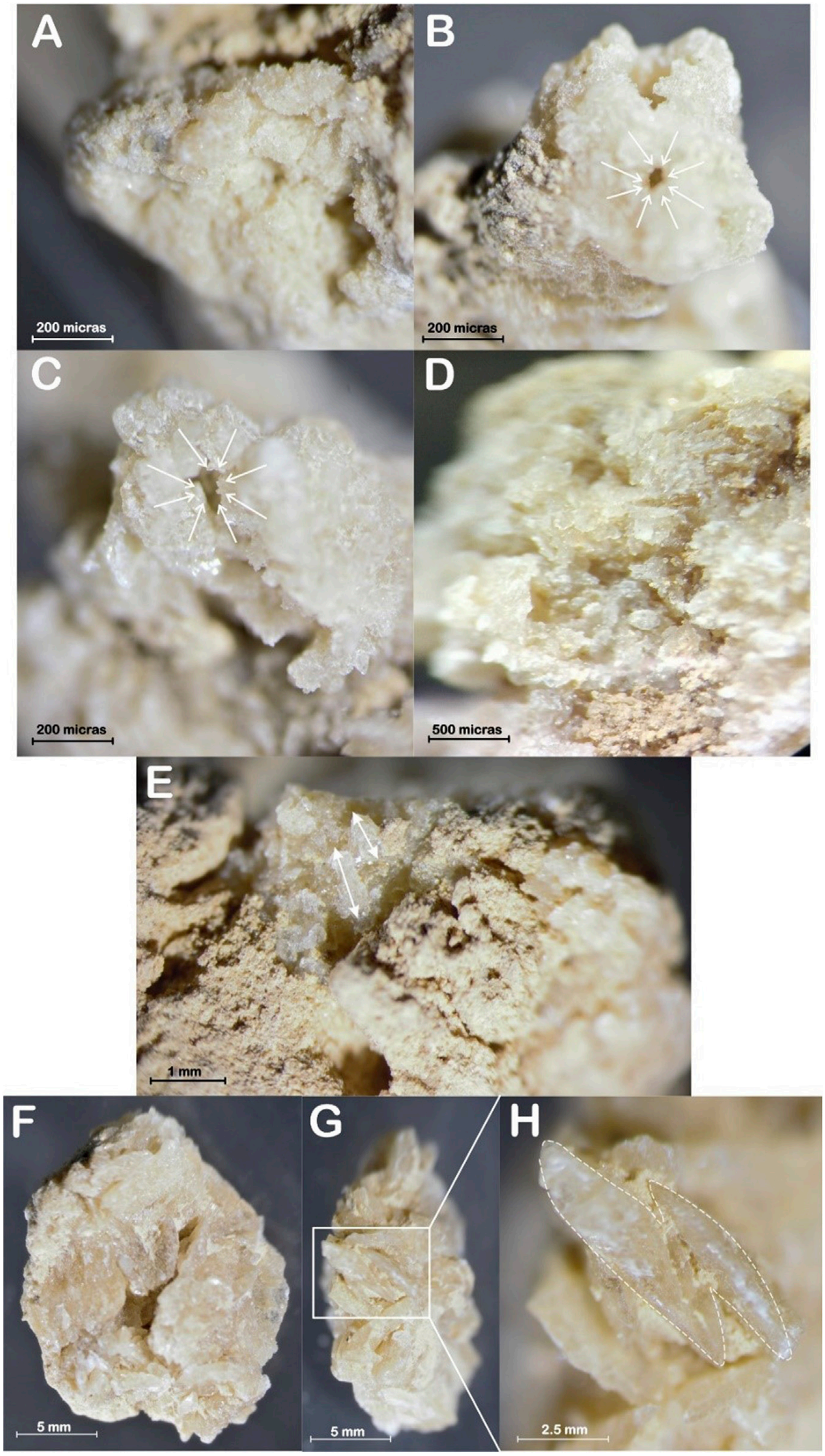

FIGURE 3 | Some examples of the size and morphology of secondary gypsum accumulations observed with a binocular, present in the profile studied. Images **(A–D)** are accumulations found in the 2Cy1 horizon. They show aggregates of small gypsum crystals (30–50 µm) with no preferred orientation. Images **(B,C)** correspond to gypsum crystal fillings in channels, with radial and central orientation (arrows indicate orientation). Image **(E)** corresponds to the 3Bwy horizon: crystalline morphologies with good development of the long axis, generating perfectly formed lenticular crystals. Images **(F–H)** correspond to the 5 Bym horizon. Images **(F,G)** are desert roses with large, lenticular (up to 1 mm) gypsum crystals. Photograph H is a detail of well-developed twinned lenticular crystals.

TABLE 2 | Results of the qualitative tests for sulphate on the three fractions and of the EC analysis (fine Earth) on a 1:5 soil:water suspension of the studied horizons.

Horizons	Qualitative sulphate test ($BaCl_2$)			EC (1:5) dS/m 25°C	% gypsum accumulations described in the field
	Total (coarse elements + fine earth)	Coarse elements >2 mm	Fine earth <2 mm		
Ap	—	—	No	0.19	0
Bw	—	—	No	0.16	0
BC	—	—	Yes	0.77	0
2Cy1	Yes	Yes	Yes	2.5	2–5
3Bw1	Yes	Yes	Yes	2.4	20–40
3Cy2	Yes	Yes	Yes	2.3	20–40
4Bwy	Yes	Yes	Yes	2.6	5–20
4Bky1	Yes	Yes	Yes	1.3	<2
4Bky2	Yes	Yes	Yes	1.6	<2
5Bym	Yes	Yes	Yes	2.6	50–60

TABLE 3 | Gypsum contents of the 3 fractions (total, coarse elements, fine Earth) following Artieda et al. (2006) and acetone method, and of the fine Earth by turbidimetry (Porta et al., 1986). Values are the mean of 3 replications ±standard error.

Horizons	Total = coarse elements + fine particles			Coarse elements			Fine particles <2 mm			
	Gypsum 40–105°C (%)	Gypsum 70–105°C (%)	Gypsum Acetone method	Gypsum 40–105°C (%)	Gypsum 70–105°C (%)	Gypsum Acetone method	Gypsum 40–105°C (%)	Gypsum 70–105°C (%)	Gypsum Acetone method	Gypsum by Turbidimetry (%)
Ap	3.9 ± 0.2	1.3 ± 0.3	—	—	—	—	3.7 ± 0.2	1.1 ± 0.4	—	0.05
Bw	3.1 ± 0.3	1.0 ± 0.2	0.07	—	—	0.07	3.1 ± 0.2	1.0 ± 0.2	0.11	0.02
BC	3.6 ± 0.3	1.3 ± 0.2	0.22	—	—	0.22	3.5 ± 0.3	1.3 ± 0.2	0.51	0.29
2Cy1	27.1 ± 0.3	23.9 ± 1.0	12.55	28.6 ± 0.3	26.1 ± 0.9	12.59	24.8 ± 0.2	25.2 ± 4.4	10.60	17.79
3Bw1	21.1 ± 0.3	17.8 ± 0.3	11.67	27.4 ± 1.1	23.7 ± 0.2	11.59	17.2 ± 0.2	14.8 ± 0.8	9.63	15.11
3Cy2	12.6 ± 0.5	9.7 ± 0.5	10.64	19.1 ± 0.4	15.4 ± 1.1	10.24	5.0 ± 0.3	3.1 ± 0.2	6.12	1.64
4Bwy	17.0 ± 0.4	13.2 ± 0.7	8.83	22.2 ± 0.7	18.7 ± 1.5	8.82	16.9 ± 0.2	14.2 ± 0.2	8.62	11.52
4Bky1	3.3 ± 0.4	1.3 ± 0.3	0.83	3.4 ± 0.2	1.6 ± 0.2	1.25	3.4 ± 0.2	2.4 ± 1.5	0.71	0.68
4Bky2	3.5 ± 0.3	1.2 ± 0.3	0.51	3.5 ± 0.4	1.5 ± 0.3	0.51	4.1 ± 0.4	1.6 ± 0.3	0.74	1.02
5Bym	53.8 ± 0.3	48.7 ± 2.2	12.40	58.7 ± 0.1	55.4 ± 0.4	12.43	52.5 ± 0.5	49.7 ± 1.1	11.02	48.64

TABLE 4 | Temperature ranges (°C) and weight (%) of the 2Cy1 and 5Bym horizons, obtained from their thermogravimetric analyses. The temperature ranges correspond to the peaks from which the weight difference (complete dehydration) has been used for the calculation of the gypsum content.

Horizon		Temperature (°C)	% Weight
2Cy1	Begin	90.12	99.21
	End	144	95.06
	Max	107.09	97.85
	% gypsum		19.83%
5Bym	Begin	91.03	99.22
	End	150.05	89.44
	max	125.08	92.15
	% gypsum		46.73%

The total gypsum calculated from the results obtained in each size fraction (fine and coarse fraction) have been compared with the total gypsum obtained from the samples without sieving (total sample), for the two temperature ranges (**Table 5**). This comparison allows us to see the goodness of the analytical method, since the results obtained are similar.

DISCUSSION

Use of the Qualitative Tests for Gypsum

The results obtained with the qualitative test show that there is no gypsum in the first 2 horizons, that is, the amount of gypsum is less than 0.26% (Porta, 1986). However, the third horizon, BC, gives a positive result in the $BaCl_2$ test, indicating that, despite having quantified a very small amount of gypsum with other applied methods, this amount is greater than 0.26%. In addition, this positive result may also be related to the existence of other sulphates that react with $BaCl_2$.

The $EC_{1:5}$ values are in agreement with the gypsum contents. In the 3rd horizon the little gypsum present does not saturate the solution although it increases the $EC_{1:5}$ by over 0.35 dS/m from the overlying gypsum-free horizons. The same occurs with the 4Bky1 and 4Bky2 horizons, with gypsum contents below 5%, but with CE values above 1 dS/m, which indicate the presence of gypsum, although they do not reach the expected values for a gypsum-saturated solution. This may be related to the high carbonate content in the whole profile (reaching 59% $CaCO_3$ in the 4Bky1 horizon), which decreases the solubility of gypsum due to the effect of the common ion (Artieda 1993). The $EC_{1:5}$

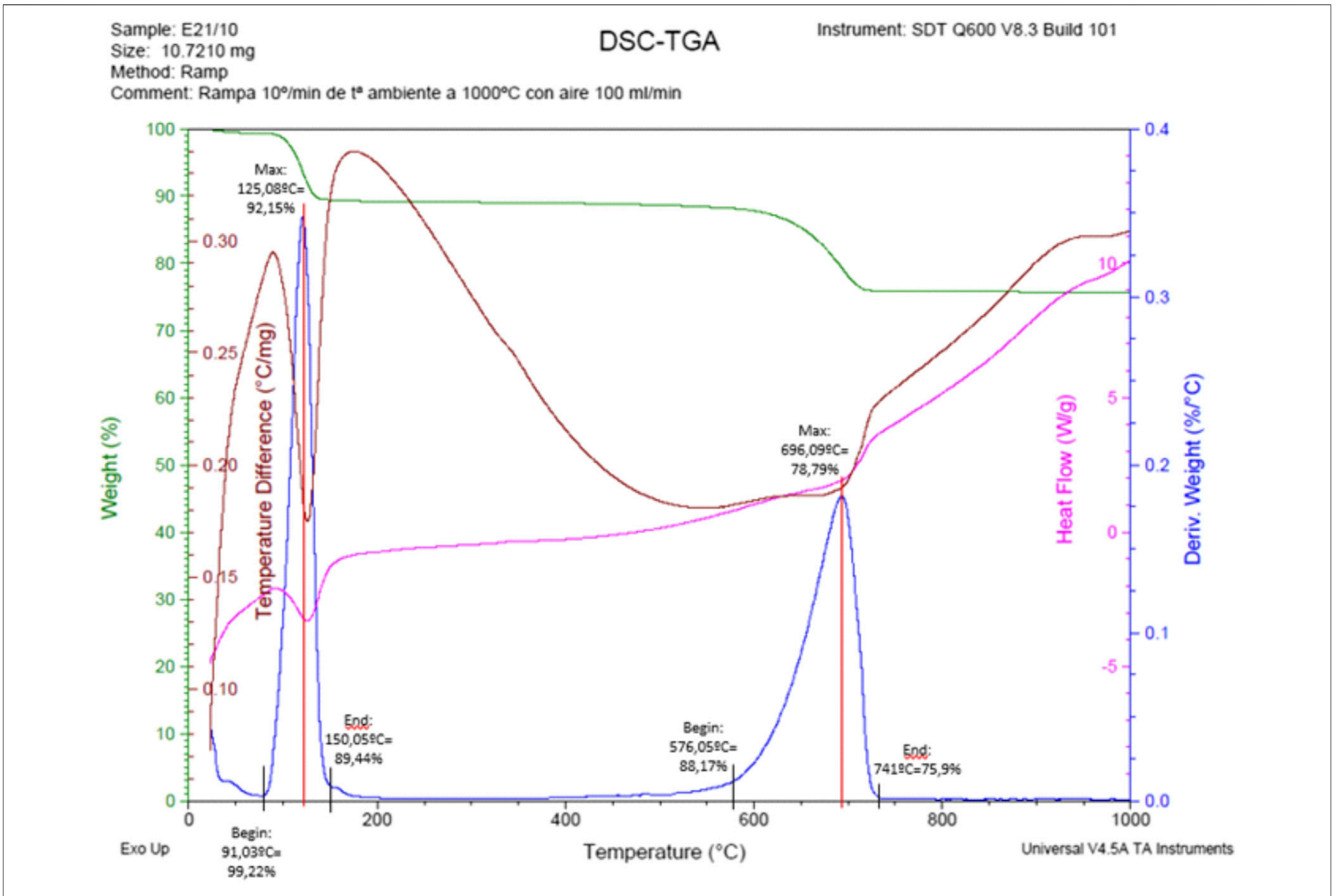

FIGURE 4 | Thermogravimetric (TGA) diagram of the 5Bym horizon (depth: 110–130 cm). The temperature peaks of gypsum and carbonate loss are indicated as red vertical lines.

TABLE 5 | Average of results obtained with the balance± standard deviation of the three measured fractions with Artieda method (40–105°C; 70–105°C). Standard deviation between results obtained from sum of gypsum in fraction and the results obtained in the total sample.

Horizons	Coarse elements >2 mm		Fine particles <2 mm		Sum of gypsum in fractions (Fine + Coarse)%		Total = coarse elements + fine particles		Standard deviation between results of sum of gypsum in fraction and total fractions	
	Gypsum 40–105 (%)	Gypsum 70–105 (%)	Gypsum 40–105 (%)	Gypsum 70–105 (%)	Gypsum 40–105 (%)	Gypsum 70–105 (%)	Gypsum 40–105 (%)	Gypsum 70–105 (%)	Gypsum 40–105 (%)	Gypsum 70–105 (%)
Ap	—	—	—	—	—	—	3.88 ± 0.2	1.33 ± 0.3	—	—
Bw	—	—	—	—	—	—	3.10 ± 0.3	1.00 ± 0.2	—	—
BC	—	—	—	—	—	—	3.57 ± 0.3	1.25 ± 0.2	—	—
2Cy1	6.97 ± 0.1	6.35 ± 0.2	18.75 ± 0.2	19.05 ± 3.3	25.72 ± 0.2	25.4 ± 3.5	27.09 ± 0.3	23.92 ± 1	1.2	1.05
3Bw1	6.24 ± 0.3	5.41 ± 0.04	13.24 ± 0.2	11.40 ± 0.7	19.48 ± 0.1	16.8 ± 0.6	21.21 ± 0.3	17.84 ± 0.3	1.4	0.7
3Cy2	4.19 ± 0.08	3.38 ± 0.2	3.92 ± 0.2	2.40 ± 0.2	8.11 ± 0.2	5.78 ± 0.4	12.57 ± 0.5	9.66 ± 0.5	3.2	2.7
4Bwy	6.15 ± 0.2	5.19 ± 0.4	12.24 ± 0.2	10.29 ± 0.2	18.39 ± 0.4	15.4 ± 0.5	17.02 ± 0.4	13.20 ± 0.7	0.8	1.6
4Bky1	0.54 ± 0.03	0.26 ± 0.03	2.88 ± 0.2	1.99 ± 1.2	3.43 ± 0.2	2.24 ± 1.3	3.33 ± 0.4	1.26 ± 0.3	0.04	0.7
4Bky2	1.19 ± 0.12	0.51 ± 0.1	2.69 ± 0.3	1.07 ± 0.2	3.88 ± 0.4	1.58 ± 0.2	3.51 ± 0.3	1.19 ± 0.3	0.2	0.3
5Bym	13.59 ± 0.02	12.85 ± 0.1	40.36 ± 0.4	38.17 ± 0.8	53.96 ± 0.4	51.0 ± 0.9	53.76 ± 0.3	58.69 ± 2.3	0.4	1.6

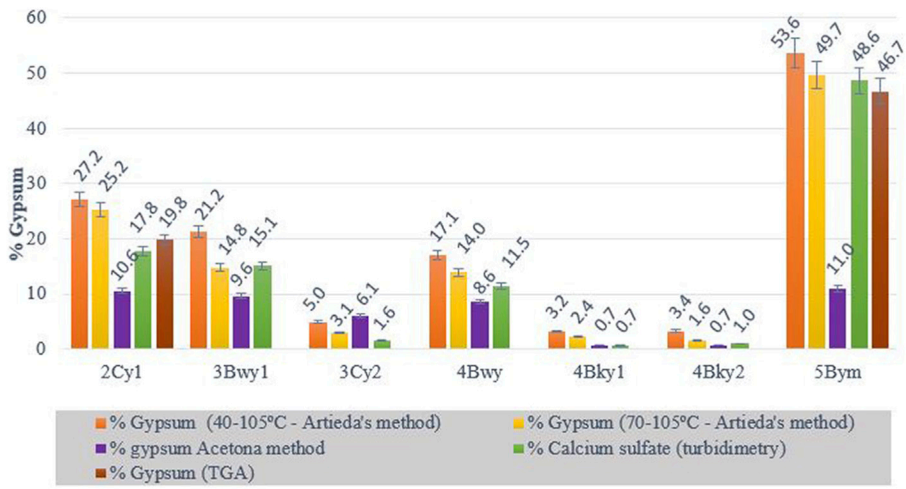

FIGURE 5 | Comparative histograms of the results for gypsum quantification according to different methods on the fine Earth fractions.

values of the other horizons with gypsum contents higher than 5% are the expected ones, between 2 and 2.5 dS/m in absence of other salts more soluble than gypsum (Lebron et al., 2009).

Comparison of the Results With the Different Methods

The results obtained with the method proposed by Artieda 1993 and Artieda et al. (2006) are generally higher than those obtained with turbidimetry and TGA, as well as the results obtained with the acetone method give significantly lower values, when the sample has a high amount of gypsum (**Figure 5**). The presence of interstratified clays (montmorillonite-illite and illite) observed with X-ray diffraction, can retain some water in the air-dried sample and this can be released by heating the sample, giving overestimated results. However, as indicated by Herrero et al. (2020), when applying the temperature range between 40 and 105°C, this loss of water from the clays does not interfere with the results.

The values obtained with the method of Artieda et al. are higher for the interval 40°C -105°C than for the interval 70°C - 105°C. Again, this may be due to the presence of residual moisture in the air-dried samples (from 2% to 6%; Porta, 1986) and to the presence of interstratified expandable clays (2%–7.2% error; Artieda, 1996). This author indicates that only half of this total moisture is lost on heating to 40°C and therefore the values may be overestimated. When heating to 70°C, the residual moisture is completely lost (Artieda et al., 2006).

These results confirm the better performance of the method when using the temperature range between 70 and 105°C, in accordance to several references (Nelson et al., 1978; Lebron et al., 2009) that state at this temperature, almost all the hygroscopic water of the gypsum is lost (Herrero et al., 2020).

The acetone method appears to be relatively accurate for low amounts of gypsum (lower than 10%, in agreement with the rest of the methods), however it presents problems in soils with high amounts of gypsum because it clearly underestimates the results. This method has several limitations in these cases, related to the loss of gypsum precipitate in the re-precipitation process, the incomplete final dissolution of the gypsum before the EC measurement, and finally, an error associated with the representativeness of the sampling, when it presents very large gypsum crystals, which is common to some of the other methods. In addition, the presence of high concentrations of other sulphates (Na and K) that also react with acetone, will cause an erroneous quantification of the gypsum.

Finally, the results obtained with TGAs are similar to those obtained by turbidimetry.

Total Gypsum Content

The results of the assessment of the total content of gyspum (**Table 5**; **Figure 5**) show a good match between the amount of gypsum quantified in the different fractions (fine Earth and coarse elements) and the amount of gypsum obtained when analyzing the gypsum in the full sample. Indeed, the differences between the gypsum contents of the unsieved sample and the one obtained after the sum of the gypsum in the fine Earth and in the coarse fragments range from 0.4% to 3%, except in the 3Cy2 horizon where the difference is 4%–5% (**Table 5**). The estimate of gypsum in this horizon is larger when considering the total sample than when analyzing the fractions separately due to the high amount of gypsum present as coarse fragments (almost half of the total volume). These results stress the importance of taking larger samples in the horizons with high proportion of gypsum in the coarse fragments, as well as of the need to carefully homogenize the samples to ensure the accuracy of the analyses. In relation to the recommended amount of sample, Artieda et al. (2006) point out that approximately 20 g of sample are needed to carry out the analyses. However, Lebron et al. (2009) mention that only 1 g of sample is needed when there is more than 30% gypsum, but 5–6 g will be necessary if the amount of gypsum is low (≈1%) (Herrero et al., 2020). In view of our results, we would recommend to follow the proposals of Artieda et al. (2006).

TABLE 6 | Classification (WRB 2014–2015 and SSS, 2014) of diagnostic horizons. Profile Mas de Caspolí (Mequinensa).

Horizon	Depth (cm)	% Percentage estimation and type of secondary accumulations	% gypsum in total Artieda method	% gypsum in total Acetone method	% gypsum in fine earth Artieda method	% gypsum in fine earth Acetone method	Classification (WRB, 2014–2015 and SSS, 2014)
2Cy1	110–130	2%–5% Vermiform gypsum, nodules and coatings of gypsum	26.84	12.55	24.92	10.60	
3Bwy1	130–170	20%–40% Very frequent vermiform gypsum, fine nodules and rhizocretions of gypsum	20.95	11.67	17.24	9.63	Gypsic horizons, according to the two main classification systems (WRB, 2014–2015 and SSS, 2014), because all of them meet the following requirements 1) ≥5% gypsum (in the total sample and in the fine earth); 2) ≥15 cm thick; 3) Product of % gypsum (by mass) by thickness (in centimeters) ≥150; 4) ≥ 1% (by volume) visible secondary gypsum accumulations
3Cy2	170–220/225	20%–40%% Very frequent vermiform gypsum	13.09	10.64	5.18	6.12	
4Bwy	220/225–338	5%–20% Very frequent –hard rhizocretions of gypsum. Frequent vermiform and nodules of gypsum. Softy powdery lime and fine nodules of carbonates	16.66	8.83	17.09	8.62	
4Bky1	338–380	<2% Few vermiform gypsum, nodules and rhizocretions of gypsum. Some softy powdery lime and fine nodules of carbonates	3.32	0.83	2.84	0.71	It does not have 5% gypsum (by mass) and therefore cannot be called a gypsic horizon (WRB 2014–2015 and SSS 2014).The name 3Bky indicates that secondary accumulations of gypsum (letter -y-) are observed in the field
4Bky2	380–405	<2% Few accumulations of gypsum, some coatings of gypsum, few hard nodules of carbonates	3.44	0.51	2.74	0.74	It has 5% gypsum, and more than 15% thickness, but the product of the % gypsum (by mass) by the thickness (in cm) does not exceed 150 and therefore cannot be classified as a gypsic horizon (WRB 2014–2015; SSS 2014)
5Bym	405–415	50%–60% Abundant subhorizontal gypsum crusts, strongly cemented, made of abundant crystals and coatings of gypsum and frequent hard gypsum nodules	53.40	12.40*	51.42	11.02*	Petrogypsic horizon according to the two main classification systems (WRB 2014–2015 and SSS 2014) according to the results of Artieda but not with the results of Acetone method* • ≥40% gypsum (by mass) (SSS, 2014) * • ≥ 5% gypsum (by mass) and ≥1% (by volume) visible secondary accumulations of gypsum (WRB 2014–2015) • ≥ 10 cm thick • It has gypsum crusts and is strongly cemented • * Acetone method results do not meet SSS-NRCS 2014 requirements

Implications for the Classification of Diagnostic Horizons and Materials

The current international classification systems, “Soil Taxonomy” (Soil Survey Staff, SSS-NRCS, 2014) and “World Reference Base for Soil Resources” (WRB 2014–2015), are not as precise with gypsum as when dealing with other soil components. This lack of precision is shown in **Table 6**, where a classification exercise has been carried out on the horizons of the studied profile based on field descriptions and gypsum quantification by Artieda method (Artieda 1993) and acetone method, reference method used in classification.

All the gypsum-containing horizons of this profile meet the requirements to be classified as Gypsic or as Petrogypsic horizons in both systems, except the 4Bky1 and 4Bky2 horizons. In this case, field observations and previous qualitative tests demonstrate the presence of gypsum, but they cannot be classified as gypsic horizons since they do not reach the minimum percentage of gypsum necessary (5% by mass), neither in the total sample nor in the fine Earth. Horizon 3Cy2 is clearly a Gypsic horizon, since it has more than 5% in both fractions, but it is at the limit when only the value with Artieda method is considered, in fine Earth. The results obtained with the acetone method also seem to support the classification, since values >5% have been obtained in all fractions of the gypsic horizons. On the other hand, the 5Bym horizon is classified as petrogypsic in the two main classification systems, according to the results obtained with Artieda. However, based on the results obtained with the acetone method, it cannot be

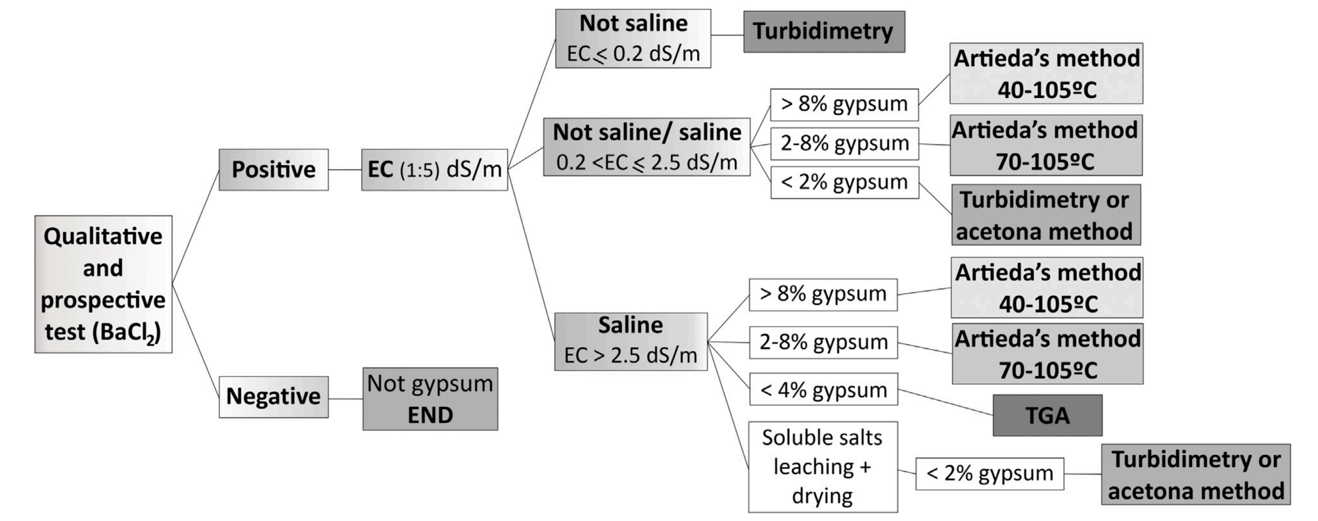

FIGURE 6 | Outline of the proposed protocol to quantify gypsum in soil.

classified as petrogypsic, in the "Soil Taxonomy" Classification system (SSS- NRCS 2014), because it does not reach the minimum gypsum required (40%)

In summary, there are different issues that should be better defined in the classification systems, to avoid misunderstandings and errors:

- Despite observing gypsum accumulations in the field, it may happen that the horizon cannot be classified as a Gypsic horizon, because it does not meet all the requirements proposed by the main classification systems (WRB 2014–2015 and SSS- NRCS 2014).
- Although the minimum limit reported in is 2% (Artieda et al., 2006), it has been observed that the accuracy clearly decreases when the gypsum content is less than 5%. This lack of precision affects the classification objective, with a minimum of 5% (WRB 2014–2015 and SSS- NRCS 2014).
- The values obtained with the acetone method are subject to several limitations, especially in the gypsum-richest materials, where this method clearly underestimates gypsum contents. This can lead to errors when soils with gypsum are classified, since the values may not meet the requirements for, e.g., petrogypsic horizons.
- The analyzed fine Earth samples may not be representative of the total gypsum when there are coarse crystals, which in addition may have a similar colour of the matrix and therefore are difficult to spot and to give visual estimations of their volume in the field.

PROPOSAL FOR GYPSUM DETERMINATION IN SOILS

After applying the different methods (qualitative preliminary test, Artieda method (Artieda 1993 and modification of the Artieda method (Artieda et al., 2006) following the recommendations of Herrero et al. (2020), besides the acetone, turbidimetric and thermogravimetric methods, a procedure is proposed to minimize the errors when analyzing gypsum soils (**Figure 6**).

It is essential to carry out a good description of the field in order to have a first estimate of the gypsum content, which will determine the method to be used. A sufficient amount of sample has to be taken in the field (minimum 500 g), and hand-sieved (care not to destroy large accumulations of gypsum) after air-drying at room temperature. Coarse fragments have to be kept if volume determination in the field has not been precise enough. The fraction to be analyzed must be crushed and homogenized, and when turbidimetry is used the sample must be pulverized to a size less than approx. 50 μm. If the acetone method is applied and there are very large crystals, it is also recommended that the sample be pulverized to reduce the measurement error associated with the behavior of this mineral (Nelson 1982).

It is advisable, in those samples that have more than 0.35 dS/m at 25°C, and especially in samples with conductivities higher than 2.5 dS/m, to carry out a previous wash with ethanol to eliminate the sulphate salts that are more soluble than gypsum. This process must be very fast (a few seconds) to avoid significant loss of gypsum. The subsequent drying of the samples is always carried out at temperatures below 40°C.

The first step is to perform a qualitative test with $BaCl_2$ 10% which detects gypsum concentrations higher than 0.26% (Porta, 1986), especially when the horizon is expected to have less than 2% gypsum (Artieda et al., 2006).

If this qualitative test gives a positive result, the electrical conductivity (1:5 soil:water) of the sample should be determined. When the conductivity is higher than 2.5 dS/m, we are dealing with a saline soil that has more soluble salts than gypsum (Lebron et al., 2009). This presence of salts invalidates the turbidimetry method, since sulphate ions can come from salts other than gypsum, causing measurement errors.

In spite of the fact that the reported precision of the Artieda method is 2% (Artieda et al., 2006), our results with different methods (**Figure 6**) indicate that in samples with low gypsum content (less than 5%) the precision is lower. Therefore, when the estimated quantity is <2%, it is not recommended to use the Artieda method (70–105°C), and if the quantity is <5%, it is advisable to use a more precise method, or to carry out a previous washing of other sulphated salts with ethanol, to increase the precision of the results.

However, when an appreciable amount of gypsum has been reported in the field, it is recommended that this method be used due to its simplicity and low cost.

CONCLUSION

The analysis of the gypsum content in 9 horizons of a loess profile in the Ebro Valley reveals that in order to achieve a good and complete characterization, the detailed description of the gypsum at different scales (field, macro, micro) is as important for its complete characterization as the method of choice for quantification in the laboratory. The protocol includes a previous good and detailed description of the field (including an estimation of the volume of gypsum), a collection of representative samples (500 g) and an adequate pre-processing of the sample (manual sieving that allows to preserve large accumulations of gypsum).

After that, two qualitative tests ($BaCl_2$ and CE to a suspension 1:5 soil:water) should be performed to determine the presence or absence of gypsum. Depending on the results, the most appropriate method (of the four proposed methods) can be chosen. If gypsum is a major component (>2%), it is recommended to use the Artieda method, based on the loss of water from the gypsum at different temperatures intervals (40–105°C; 70–105°) due to its simplicity and low cost. If the amount of gypsum expected is less than 8%, only the temperature range between 70 and 105°C should be applied. When gypsum is a minor component in the field description (<2%) and the qualitative test is positive, another more precise method is advised. In this case, a thermogravimetric analysis is proposed when the samples are saline ($EC_{1:5}$ > 2.5 dS/m at 25°C), or a turbidimetric analysis, which of the four methods applied is the most precise, but also the most complex. Furthermore, if this method is to be applied to saline samples with conductivities greater than 2.5 dS/m, it is necessary to remove sulphated salts by other means before the analyses.

For its part, the acetone method, the reference method used in the main classification systems (SSS- NRCS 2014 and WRB 2014–15), although it seems to give correct values for low amounts of gypsum (i.e. less than 15%), it is clearly inaccurate when gypsum is the main component of the horizon, since it underestimates gypsum contents. In addition, the results can be erroneous if the sample contains other sulphates that react with acetone.

We demonstrate that gypsum can be fully quantified using relatively simple and cheap procedures, and that this quantification is sufficiently precise for many purposes. However, when methods capable of detecting very low amounts of gypsum (less than 2%) are required, more complex and expensive methods such as acetone, turbidimetry or thermogravimetry will have to be chosen.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

DA: Carrying out laboratory analyses, obtaining results and writing the manuscript. MA: Collaboration with laboratory analyzes and help in the revision. SP: Collaboration with laboratory analyzes and help in the revision. RRO: Field description and help in the final writing. JRO: Field description and help in the final writing. RMP: Tutoring and guide of the paper.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/sjss.2022.10669/full#supplementary-material

Supplementary Table S1 | Types of gypsum accumulations in soils (partly based on Poch et al., 2018).

Supplementary Table S2 | Selected field and chemical characteristics of the horizons of the Mas de Caspolí (Mequinensa) profile (CBDSA, 1983).

Supplementary Table S3 | Percentage and average of fractions of fine earth (<2 mm) and coarse fraction (>2 mm) of the studied horizons.

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