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IMPLEMENTATION OF RECLAMATION TECHNIQUES IN AGRICULTURAL STONY SOILS FOR THE OPTIMIZATION OF PRECISION FARMING SYSTEMS

Settore scientifico-disciplinare

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1. Preface

Conventional, integrated, organic, biodynamic, sustainable, conservative...

The evolution of cultivation methods in income farming has led to the definition of various cultivation systems or models, time-to-time developed according to political, market or social needs and sometimes adopted ignoring or neglecting their long-term effects and consequences or their actual compatibility with crops characteristics or environmental sustainability of cultivation areas.

Thus, the often-indiscriminate use of synthetic fertilizers and pesticides, while it has allowed crop yields maximization in the short term, it has also led to the destabilization of agroecosystems and the depletion of organic soil fertility. The result has been a general flattening and even decreased soils productivity, with the consequent widespread increase of desertification processes, sometimes also compromising the products wholesomeness.

On the other hand, totally relinquishing the use of synthetic agrochemicals, in the name of questionable quality and authenticity indices, would be difficult to reconcile with agro-industrial crops profitability, which is the ultimate, if not the only, reason for the committing resources and capital in productive agriculture.

The main goal for agricultural operators should be the ability to mediate between these extremes, or to reconcile the profitability of the cultural activities, in terms of crop results maximization, with environmental sustainability, products quality and wholesomeness.

Whatever the type of agriculture, the primary importance factor of the cultivation success is an adequate soil management since soil is the medium where plants are physically located and from which they draw most of their vital nutrients [1.1].

Among these management practices, soil tillage techniques are the most important because they deeply modify the physical-chemical and biological structure of the soil, also affecting crops growth.

Tillage practices are usually classified into two groups: conventional and conservative tillage systems.

In conventional tillage, primary and secondary operations are normally performed for seedbed preparation and cultivation of a given crop. In primary tillage, deep tillage operations consist in using ploughs, chisels, and/or subsoilers; while shallower tillage is applied in secondary tillage operations to refine the soil and prepare the seedbed for planting.

Conservative tillage is defined as “any tillage system in which at least 30% of the soil surface is covered by plant residue after planting to reduce erosion by water or wind” [1.2], avoiding deep soil layer inversion and burying crop residues.

There are five types of conservative tillage systems: no-tillage, mulch tillage, strip (zonal) tillage, ridge tillage and minimum tillage. The main principles of the conservation tillage methods entail minimum mechanical soil disturbance, permanent organic soil cover, and diversification of crop species grown in sequence or in association [1.3].

Conservative tillage systems have advantages for both soil and water resources, with positive effects on time and fuel savings, improving water infiltration and soil moisture, decreasing erosion and soil compaction, enhancing soil biological activity, reducing the release of carbon gases, and air pollution [1.4]. Conservative tillage systems are usually considered more sustainable cultivation practices, but they also have some disadvantages.

Their main drawbacks are:

- increased soil pest’s populations,
- transfer of insect pests and diseases from the crop residues to the next crop,
- increase of herbicide usage to control weeds competing with the main crops.

In advanced conventional tillage methods, soil tillage is based on the variation in soil conditions and properties, whose goals are to use less fuel and energy and prevent excessive soil disturbance. These advanced tillage methods are named as variable depth tillage, site-specific or precision tillage, in which it is possible to vary the soil tillage depth according to the data from a data source, either a variability map or a real time sensor; therefore, this method is called Map-Based or Sensor-Based Site-Specific Tillage [1.5].

Any soil processing operation, which is considered necessary in the different phases of the crop cycle must, therefore, be rationally planned and correctly executed, both to maximize its effects limiting negative impact and for time and operating costs optimization, in order to reconcile and satisfy the needs of: *i*) the crop, which draws support and nutrition; *ii*) the environment, since soil is a non-renewable resource, easily subject to degradation by anthropogenic pressure; *iii)* the business economics, which conditions cultivation structures and operating methods, also according to production guidelines (e.g., in Italian, DOC, DOP, IGP, IGT).

Productivity and sustainability are, therefore, the two key factors for the long-term profitability of farm management, but they require specific and diversified technological approaches according to the agroecological, economic and social conditions of the cultivation areas, to achieve marginal productivity in the use of production factors [1.6], while respecting environmental sustainability principles of specialized income crops.

1.1. Sustainable Agriculture

Many years ago, agricultural sustainability was considered a basic requirement for human survival. The concept of sustainable agriculture has been discussed for several decades and has focused on four general aims: sufficient food and fibre production, environmental stewardship, economic viability, and social justice, as shown in Figure 1.1 [1.7].

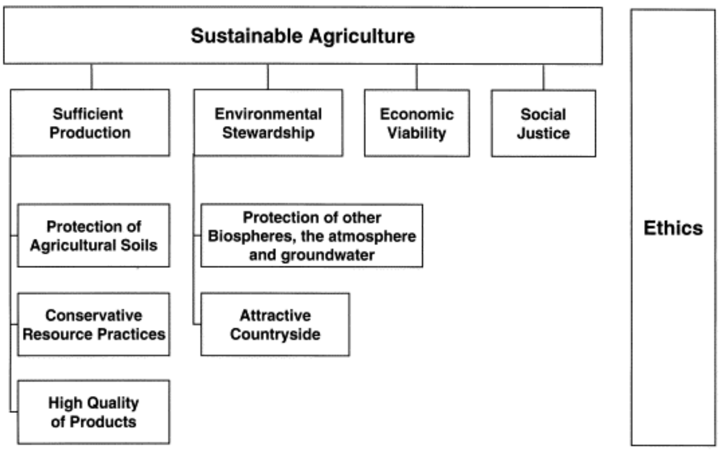

Figure 1.1. Integration of quality components into the overall aims of sustainable agriculture. Ethics are added as an independent but all-encompassing factor [1.7].

The term ‘‘*sustainability*’’ originally referred to agricultural and industrial technologies that reduced or prevented the environmental degradation often associated with economic activity. In 1972, the United Nations defined sustainability as *‘‘...aimed to meet the needs of the present without compromising the ability of future generations to meet their own needs*’’ [1.8]. Applying this concept to agriculture, the American Society of Agronomy [1.9] defines ‘‘*Sustainable Agriculture as something that, over the long term, enhances environmental quality and the resource base in which agriculture depends; provides for basic human food and fibre needs; is economically viable; and enhances the quality of life for farmers and the society as a whole*’’ [1.10].

More recently, the term “*sustainability*” has been associated with the concept of “*net zero*”; however, while the perception of the public is that we should not use more resources and release more pollutants, to far-sighted thinkers the concept of "net zero" is not enough, because it does not solve the problem: it should be aiming for "*net positive*" [1.11].

Given that agriculture is the most important tool on which the future of our planet depends upon, the greatest attention should be mainly focused on agriculture, in terms of commitment of technological resources, also given the forecast of world population growth to somewhere between 9 and 10 billion by 2050, which would entail a 70% increase in food production [1.12]; while land consumption advances and continues to generate an irreversible loss of environmental resources and ecosystem functions at a global level. This leads to a high reduction of biodiversity and productivity and compromises the availability of resources, due both to anthropization (overbuilding), human activities and unsustainable use choices that contribute to soil degradation (e.g., climate change, drought, SOC loss, desertification, desertization) [1.13 - 1.15].

The United Nations Convention to Control Drought and Desertification (UNCCD) [1.16] adopted the following definition of desertification: *land degradation as arid, semi-arid, and dry sub-humid areas, attributable to various causes, including climate changes and human activities*.

This definition means that desertification is a phenomenon that affects areas characterized by ecologically fragile ecosystems, where the soil is threatened by a series of causes such as drought, erosion, fires, changes in rainfall patterns, unsuitable agronomic practices, overgrazing, excess tourism, soil pollution and erosion. In fact, even with no rainfall patterns variation, the soil thinning caused by inadequate agronomic practices and erosion, progressively reduces the amount of water that the soil can store, resulting in the soil reacting as if it were in an arid environment.

Therefore, desertification means the decrease in the biodiversity of non-irrigated cultivated land, with a consequent decrease in biological and economic productivity. Instead, the term that most identifies the common imagination is the desertization, namely "turning into desert", and is the cause of the expansion of sandy and stony deserts in areas of the planet with torrid temperatures and low rainfall, but also caused by soil degradation phenomena, caused by excessive grazing and inadequate agronomic practices.

During the second half of the 20th century, a very pronounced decline in soil organic carbon (SOC) contents was in facts observed, both in agricultural and non-agricultural land cover (Figure 1.2) [1.17].

Figure 1.2. Soil Organic Carbon Content (%) in the surface layers of European soils.

According to the 2022 SNPA report [1.18], Italy has a land consumption level among the highest in Europe: with an average of 19 hectares per day, the highest value in the last ten years, and a speed over 2 square meters per second, in 2021 land consumption is close to 70 km^2 of new artificial covers in a single year. Cement now covers 21,500 km^2 of national soil, 5,400 of which, a territory as large as Liguria, comprising only buildings.

Between 2006 and 2021 (Table 1.1) Italy lost 1153 km^2 of natural or semi-natural soil, with an average of 77 km^2 per year, mainly due to urban expansion and its collateral transformations as loss of green areas, biodiversity and ecosystem services, and soil impermeabilization that increase flooding and heat waves, with an economic damage estimated at almost 8 billion euros per year.

Table1.1. Speed of net daily land consumption over the last 15 years source: ISPRA on SNPA cartography [1.18]

Years	Daily land consumption (ha/day)	Daily land consumption revised* (ha/day)
2006-2012	27.4	28.7
2012-2015	15.1	15.2
2015-2016	14.4	14.7
2016-2017	15.4	15.6
2017-2018	16.7	17.1
2018-2019	16.1	17.2
2019-2020	14.2	15.9
2020-2021	17.3	-

* Updated estimates based on land consumption in 2022 from high-resolution satellite images

Even though during the last century, mechanization, synthetic fertilizers and pesticides and plant breeding have increased productivity and made crop production possible also on previously uncultivated land, it is very unlikely that such technologies will be able to meet the food needs of an ever-growing human population, if we do not become aware of the limits of soil productivity, avoiding incoherent and hypocritical rants on the environmental sustainability of "organic crops" or "ecological transitions"; and, on the other hand, in the absence of effective strategies to curb population growth and its irreversible damage on the environment, as poignantly described by Agent Smith (actor Hugo Weaving) in the movie "Matrix" (1999) [1.19]:

"I'd like to share a revelation that I've had during my time here. It came to me when I tried to classify your species and I realized that you're not actually mammals. Every mammal on this planet instinctively develops a natural equilibrium with the surrounding environment but you humans do not. You move to an area, and you multiply and multiply until every natural resource is consumed and the only way

you can survive is to spread to another area. There is another organism on this planet that follows the same pattern. Do you know what it is? A virus. Human beings are a disease, a cancer of this planet. You're a plague."

This assumption clashes with the commonly accepted definition of "sustainability", as the characteristic of a process or a state that can be maintained at a certain level indefinitely in time and space, so much so that the inability of planet Earth to meet the needs of humanity and the ecological risk associated with population growth was postulated back the 1970s. Biologist Paul R. Ehrlich has quantified its effects in the "IPAT" formula (I = P x A x T); where: I= total impact; P= population; A= affluence (availability of well-being and economic growth); T= technology. This equation is adaptable to any factor of production, process or state as conceived by the previous definition of sustainability. E.g., for the incidence, or impact, of vehicle fuel, the formula considers the parameters shown in Figure 1.3 [1.20]. Based on global estimates, in his view, "… *We must improve our environmental performance on goods and services by 5% a year just to stay even"* (in 1972!).

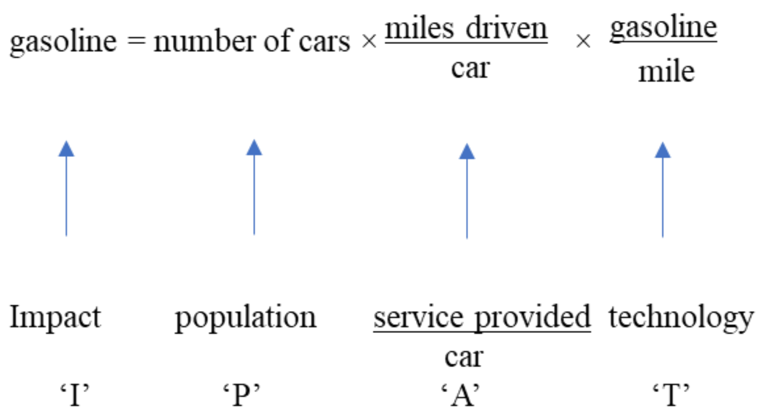

Figure 1.3. Example of IPAT applied to the Gasoline Used in Automobiles

In 1983, following a resolution by the United Nations General Assembly, the World Commission on Environment and Development was established to develop a "global agenda for change". The Commission, chaired by the Norwegian Gro Harlem Brundtland, published in 1987 the Brundtland Report, which introduced the theory of sustainable development [1.21].

According to this theory, Environment and Development are closely connected and interdependent realities: development cannot exist if environmental resources are deteriorating, just as the environment cannot be protected if the economic relevance of the environmental factor is not computed into growth.

Humanity would then have the possibility of making development sustainable, that is, of ensuring that it meets the needs of the present generation without compromising the ability of future generations to respond to theirs. However, the concept of sustainable development implies certain crucial objectives for environmental and development policies, including, in particular:

- meeting essential needs in terms of jobs, food, energy, water, and hygiene;
- ensuring a sustainable demographic level.

The history of humankind teaches us that – except perhaps in the Amish communities and in some uncontacted tribes, or between the Na'vi of Pandora planet (Avatar movie) – the prevailing behavior of all the dominant ethnic groups, in all ages, has always been, and is in fact still today, the one described by Agent Smith.

In a market-economy industrial society, the average individual consumes 80 times more energy than an inhabitant of Sub-Saharan Africa. To bring the energy consumption needed to satisfy the "basic needs" of developing countries to the level of industrialized countries, current global energy use is expected to increase fivefold by 2025; an unrealistic situation for our planet ecosystem, unless we resort to higher energy efficiency systems, for the production and operating of devices essential to the - for the most part superfluous - needs of industrialized populations.

On the contrary, in this scenario, the rise of the Global Hunger Index (GHI) [1.22, 1.23] is more plausible in an increasingly large part of the world's "industrialized" population - also given the increasingly intensity of migration flows [1.24] - with increasing discrimination between ethnic groups and social classes that will be able to enjoy quality and nutritionally viable food, and others, much more people, forced to feed on insects, already touted as "*sustainable food*" or "*food of the future*" or "*perfect candidates for ecological and sustainable food*" from multiple sources [1.25 - 1.28], with the global market for edible insects that is expected to reach approximately USD 8 billion by 2030 [1.29]; as well as rodents, which are already food source for many cultures in various parts of the world [1.30].

Concurrently, it is not plausible to increase crop productions of the forecasted 70%, only with a "*sustainable productions enhancement*", also using the newest genetic technologies, generally known as "*genome editing*", "*genomic breeding*", "*new OGM*", "*speed breeding*", or also "*New Breeding Techniques (NBT)*", in Italian: *Tecnologie di Evoluzione Assistita (TEA)* [1.31 - 1.33].

At present, the near future of human food seems to be that provided by the "Super Sprout Factories" [1.34].

It is peculiar how such food shortages conditions are generally attributed to famines, wars, epidemics, ignoring, or rather almost intentionally avoiding any mention of overpopulation as the primary cause of world hunger.

In these conditions, or despite them, it is however mandatory to continue to work for the conservation and recovery of agricultural areas that are abandoned or not adequately managed, from crops selection and management optimization to the evaluation of the agronomic usefulness of some of available agricultural reclamation systems usefully adoptable in the different agricultural contexts, for the restoration of physical, chemical, and biological fertility of arable lands. This also to allow the implementation of the most modern technologies of 4.0 agriculture [1.35, 1.36] in precision farming systems, to maximize production yields, contain production costs and reduce the environmental impact of agro-industrial crops, with the aim to contribute to achieve the "NET positive" balance of the future agriculture.

1.2. Precision Agriculture

The cultural and managerial multiplicity of income agriculture involve a corresponding variety and diversification of technical and methodological approaches to maximize profitability, in compliance with environmental protection and productive processes sustainability.

The effectiveness of these approaches can be maximized by planning operations according to the different site-specific needs of the crop, adopting and adapting technologies and methods based on special prescription maps indications produced by specific databases relating to georeferenced crops.

Precision Agriculture is part of this logic, whose implementation in production systems is configured in the acquisition of agri-environmental parameters, and in the evaluation of their spatial-temporal variability to define, after analysis of site-specific data, a decision support system for the entire company management aimed at the execution of agronomic operations considering the cultivation needs and the biochemical and physical characteristics of the soil [1.37].

Precision agriculture, therefore, aims to increase management efficiency of agriculture, as development of recent technologies, modification of old ones and integration of monitoring and computing activities at farm level to maximize the cultural results.

For Bongiovanni and Lowenberg-Deboer [1.10], the Site-Specific Management (SSM) concept can be resumed as doing "*the right thing, at the right place, at the right time"*. This idea is as old as agriculture itself, but during the mechanization of agriculture in the 20th century there was strong economic pressure to treat large fields with uniform agronomic practices. Precision farming supplies a way to automate SSM using information technology, thereby making SSM practical in commercial agriculture. PA includes all those agricultural production practices that use information technology either to tailor input to achieve desired outcomes, or to monitor those outcomes (e.g., variable rate application, yield monitors, remote sensing).

Various definitions have been conceived by many Authors; some of which are non-exhaustively reported as:

Lowenberg-DeBoer and Swinton [1.38] also defined SSM as the ''*electronic monitoring and control applied to data collection, information processing and decision support for the temporal and spatial allocation of inputs for crop production*''. They highlight that the focus is on agronomic crops, but the arguments apply also to horticultural crops and electronic tagging of livestock.

Pierce and Nowak [1.39] defines Precision Agriculture as the application of technologies and principles to manage spatial and temporal variability associated with all aspects of agricultural production for the purpose of improving crop performance and environmental quality.

For Kirchmann, and Thorvaldsson [1.40], Precision agriculture is a discipline that aims to increase efficiency in the management of agriculture. It is the development of new technologies, modification of old ones and integration of monitoring and computing at farm level to achieve a particular goal.

For Tey and Brindal [1.41], Precision Agriculture is a production system that involves crop management according to field variability and site-specific conditions. Precision agricultural technologies are those technologies which, either used individually or in combination, as the means to realize precision agriculture.

For McBratney et al. [1.42] the definition of precision agriculture is still evolving as technology changes, and we become more aware of what is achievable. One generic definition could be ”that kind of agriculture that increases the number of (correct) decisions per unit area of land per unit time with associated net benefits”.

Precision Agriculture potentially provides producers improved tools to manage those inputs that must be brought to the farm. Instead of indiscriminately applying fertilizer or pesticides at uniform rates over large areas, PA allows producers to better target applications. It is often argued that PA substitutes information and knowledge for some external physical inputs, thereby potentially moving the farm closer to the ideal of biological balance. Of course, information technology and knowledge that makes PA work are also external inputs. The hope of PA is that its use will be less disruptive of natural systems than the uniform application of physical inputs.

In summary, the main stages of precision agriculture are: *i)* collection of data through wireless sensor networks or drones to get information on environmental parameters of the area of interest, weeds, pests, plant diseases, or harvest conditions; *ii)* data analysis for the definition of operation plans through DSS (Decision Support System) software systems, e.g., to correctly setting the doses and intervals of irrigation, pesticides, fertilizers, sowing rate; *iii)* monitoring the effects on the harvest; for the main goal of optimizing agricultural management efficiency.

However, the efficiencies of agricultural soil management systems are strongly conditioned not only by soil texture, but also by the presence of coarse fractions (skeleton) in the cultivation layer. These fractions, even if not contemplated in the composition of the fine earth of the soil, being considered an inert fraction, can interfere with the cultivation needs, damage the machinery, penalize the seedbed quality, and require more energy and attention in tillage operation; till to making the use of some cultivation machines – in particular in the horticultural sector – impractical. In these conditions, it becomes necessary to proceed with the coarse fractions removal to optimize the cultural management according to modern soil cultivation techniques.

In this context, the goal of this project is to evaluate/validate a reclamation technique of stony soils, for the long-term improvement of the structural and textural characteristics of the arable layer, to optimize operative efficiency of PA cultivation machines, and maximize crops profitability in terms of both yield increase and cultivation costs reduction.

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2- The Stony Soils Reclamation Systems in Agricultural Lands: A Review

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Abstract

The agricultural soil is a highly variable and complex active medium for the plant's life. Due to prolonged formation processes, it must be considered as a non-renewable resource, easily subject to many degradative processes, in most cases due to human activities. These activities lead to the definition of "anthropic" soils, often labelled also as "disturbed", "manipulated", "artificial", or "deviations" of the natural soil continuum. In the agronomic sense, however, when these deviations result from the optimization of structural characteristics of fine earth fractions, they may represent the main quality parameters of soil in terms of physical, chemical, and biological fertility. Nevertheless, over the fine earth fractions, many agricultural soils have a variable percentage of varying coarse fractions in their arable layer, interfering with cultivation needs, damaging machinery, and requiring extra energy and time for soil tillage. They may even make the use of machinery impracticable. When these conditions occur, it becomes necessary to proceed with soil destoning to recover arable land and optimize the cultural management according to modern farming techniques and machines for soil cultivation. This review briefly summarizes the soil destoning techniques currently available for agricultural lands: i) the collection and removal of stones from the field; ii) the on-site stones crushing; iii) the stone burial.

Keywords: Agricultural Sustainability; Soil Quality; Stoniness; Soil Destoning Systems

2.1. Soil Origin, Definitions, and Classifications

Soil is a highly complex and variable active medium made of mineral particles, organic matter, water, air and living organisms. It stands for the natural habitat for the gene pool and the growth medium for plants' life, and it results in being the food, biomass, and raw materials provider for human activities. Soil also stores, filters, and transforms many substances, including water, nutrients, and carbon [2.1]. Such functions (e.g., producing biomass, acting as a carbon store) are crucial for food production, climate regulation and adaptation, carbon sequestration, water filtering, and biodiversity preservation [2.2, 2.3].

Soil is prone to many degradative processes and threats (i.e.: erosion, mineralization of organic matter, destructuration processes, lack of biodiversity, floods, and landslides). Because of the prolonged soil-forming process resulting from specific climate conditions, geomorphology, the composition of parent materials, biotic activity, and human influence, it shall be considered a non-renewable resource.

Combinations of degradative processes are the factors most responsible for variable grades of desertification phenomena [2.4]. Soil formation begins with the exposure of the rock layer to the altering action of environmental agents. Such action reduces it into smaller and smaller fragments that, combined with other particles and following the interaction with the vertical water flow [2.5], gradually give rise to the stratigraphy of various layers (horizons) that stands for the soil profile. Soil horizons differ in terms of many features, e.g., color, thickness, chemical composition, physical properties, biological activity, and pH [2.6].

Various classification systems were developed throughout early human history to distinguish among the soils important to human lives [2.7]. In 1862, Fallou coined the term pedology for the scientific study of soils, and around 1870, Dokuchaev developed the fundamentals of soil investigation, introducing a new concept of soils as independent natural bodies, each with its morphology caused by a unique combination of climate, living matter, earthy parent materials, relief, and age of landforms [2.8].

Being the soil system constantly evolving, Jenny [2.9] conceived the Equation (1) that represents the most well-known model of soil formation describing the soil (S) resulting from the interaction of biotic and abiotic factors such as climate (cl), organisms (o), relief or topography (r), parent material (p), time (t), and other not specifiable forces (...):

$$S = f\,(cl, o, r, p, t) \qquad (1)$$

The acronym CLORPT means that soil-forming factors are independent of a soil system and vary in space and time. In addition, the not specifiable forces of the model include human activities, which in most cases are those having the highest impact on soil structural characteristics so that the resulting soils are often labelled as "disturbed", "artifacts", "manipulated", "artificial", and considered more as "deviations" rather than a part of the soil continuum [2.10, 2.11, 2.12].

Based on the CLORPT model of soil formation, McBratney *et al.* [2.13] formulated the SCORPAN model represented by the Equation (2):

$$Sc/Sa = f\,(s, c, o, r, p, a, n) \qquad (2)$$

Here, soil classes and soil attributes (*Sc/Sa*) result from the interaction of soil (*s*), climate (*c*), organisms (*o*), topography (*r*), parent material (*p*), age (*a*), and spatial position (*n*). The SCORPAN approach allows the quantitative prediction of soil classes or continuous soil attributes based on empirical observations: it does not explain the factors of soil formation. In addition, the soil itself can be used as a factor because it results from the characterization of its properties or soil properties from its class or other properties. Minasny *et al.* [2.14] reviewed and listed the past studies using the SCORPAN approach.

2.2. The World Reference Base

In 1998, the World Reference Base (WRB) [2.15] replaced the FAO/UNESCO Legend for the Soil Map of the World [2.16] as the international soil classification standard. It classes the soil as "*any material within 2 m from the Earth's surface that is in contact with the atmosphere, with the exclusion of living organisms, areas with continuous ice not covered by other material, and water bodies deeper than 2 m*"; and defines it as: "*a continuous natural body which has three spatial and one temporal dimension*", represented by the hires:

- formed by mineral and organic constituents and includes solid, liquid, and gaseous phases;

• constituents, organized in structures specific to the pedological medium, form the soil's morphological aspect and result from the history of the soil cover and its actual dynamics and properties;

• constantly evolving, so its fourth dimension is time.

However, the soils resulting from the interaction with anthropic activity (anthrosols) still present one of the most significant classification challenges: they currently represent more than 3000 soil names at the highest levels of world soil taxonomy (Figure 2.1) [2.17], of which more than 320 major soil types have identified in Europe alone, differing significantly each other in physical, chemical, and biological properties [2.18, 2.19, 2.20, 2.21].

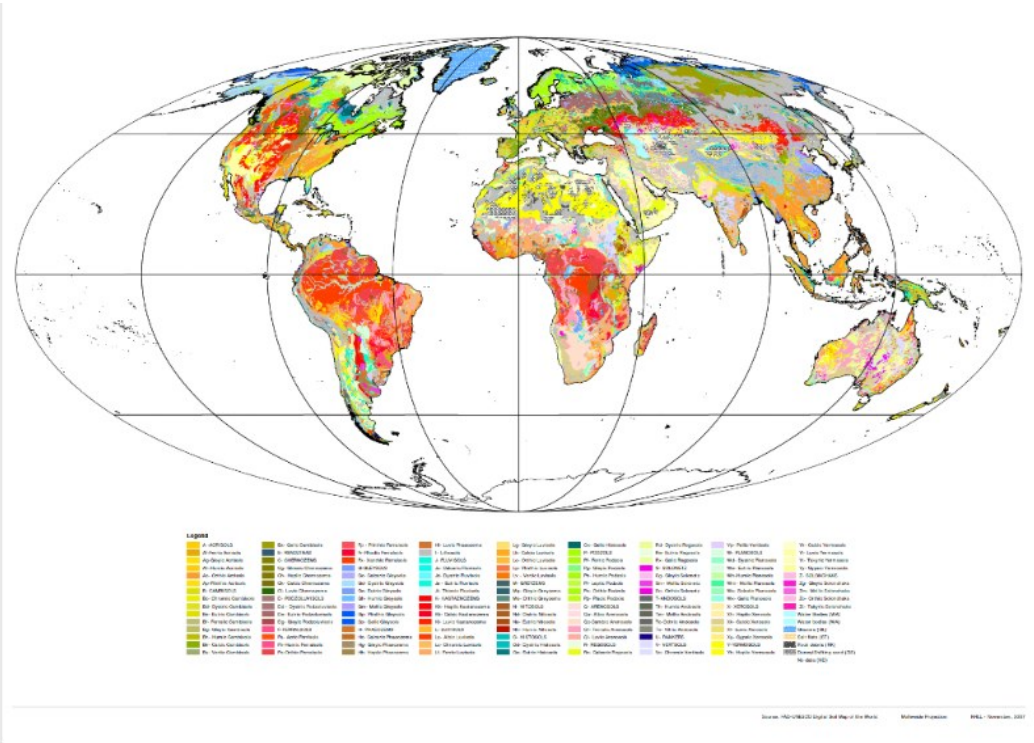

Figure 2.1. FAO-UNESCO Digital Soil Map of the World

2.3. Soil Horizons

A soil horizon is a layer commonly parallel to the soil surface, whose properties differ from those of the adjacent overlying and underlying horizons such as color, structure, texture, and rupture-resistance class. Soil master horizons are usually named with the capital letters, with the addition of lowercase letters suffixes to denote other characteristics [2.18].

In agricultural soils, the horizon identification usually is limited to defining, from top to bottom, the A, E, B, C, and R horizons (lower layers are characterized by a higher density and lower organic matter content than the upper layers).

The "A" identifies the surface mineral horizon with organic matter (humus) accumulation, also named "topsoil". "B" defines a subsurface soil structure, also called "accumulation" or "illuvial" horizon. The "C" corresponds to the parent material, with little or no pedogenic alteration, or still unaltered by soil forming processes. When present, the "E" horizon, also called "eluvial", is lighter in color than the "A" horizon above or the "B" horizon below. The "R" layer refers to the bedrock, which represents the worst-case scenario in agricultural land use and crop management if close to the soil surface [2.5].

2.4. Topsoil Structure and Texture

Soil structure refers to the organization and arrangement of soil particles and their resultant porosity. It is a composite soil quality that exerts significant control on most physical, chemical, and biological processes that occur in both natural and anthropic soils, including transport and storage of liquids, gases, and heat, root penetration and proliferation, microbial life, and the decomposition and storage of organic soil matter.

Soil texture refers to the percentage distribution by weight of their elementary particles, of diameter size less than 2 mm. These particles, distinguished as sand (0.05 to 2 mm), silt (0.002 to 0.05 mm), and clay (less than 0.002 mm) constitute the fine earth of soil, that is defined based on the prevalence of one of these fractions, as indicated in the texture triangle (Figure 2.2) [2.22].

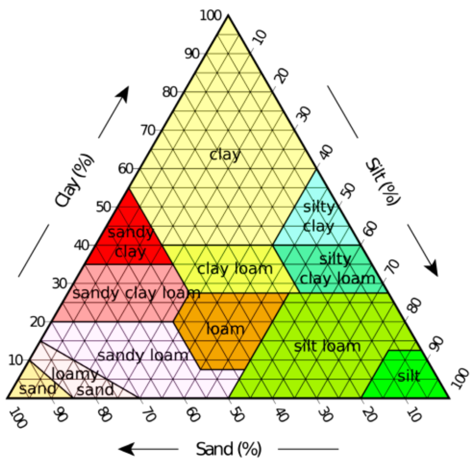

Figure 2.2. Soil texture triangle based on USDA particle-size classification.

In agronomy, soil structure also refers to the quality of topsoil, or active layer, in terms of water holding capacity, ease of tillage, and suitability for root growth and microbial life, which relates to crop growth and productivity and their variations/evolutions according to different types of soil management [2.23 - 2.27].

In cultivated soils, the topsoil, or active layer, is defined as the A horizon only, while the E, B, and C horizons compose the subsoil, or inert layer, forming the cultivation profile of the soil. Consequently, topsoil is more sensitive to environmental conditions and changes than other parts of soil profiles. Accordingly, thin topsoil sections show microstructures, organic matter types, and features related to faunal activity or specific environmental conditions and cultivation techniques [2.28, - 2.31], that contribute to determining the quality index of the topsoil as per Table 2.1.

Table 2.1. Topsoil quality index

Category	Soluble salts (dS/m or mmho /cm)	pH	Sand (%)	Silt (%)	Clay (%)	Texture class*	O. M. (%)	% Coarse fragments (> 2 mm in diameter) **	Sodium Adsorption Ratio (SAR)*
Ideal	< 2	5.5 to 7.5	< 70	< 70	< 30	L, SiL	>=2.0	<= 2	< 3 for any texture
Acceptable	< 4	5.0 to 8.2	< 70	< 70	< 30	SCL, SL, CL, SiCL	>=1.0	2.1 to 5.0	3 to 7 (SiL, SiCL, CL) 3 to 10 (SCL, SL, L)
Unacceptable	> 4	< 5.0 or > 8.2	> 70	> 70	> 30	LS, SC, SiC, S, Si, C	<1.0	> 5.0	> 10 for any texture

* - L = loam; SiL = Silt loam; SCL = sandy clay loam; SL = sandy loam; CL = clay loam; SiCL = silty clay loam; LS = loamy sand; SC = sandy clay; SiC = silty clay; S = sand; Si = silt; C = clay.
** - This guideline also includes no fragments larger than 1 ½ inch (381 mm) in diameter.

2.5. Soil Quality

Many Authors have given various descriptions of the soil quality concept, most frequently referred to as soil agricultural destination and the active layer's physical, chemical, and biological fertility [2.32 - 2.35]. Among these, those referring to soil quality either as its "*capability to function within an ecosystem and positively interact with the environment*" [2.36]; or the capability to "*receive, store, and recycle water, minerals, and energy to support plant production at optimal levels, while preserving the health of the environment*" [2.37]; or as the "*integrated measure of both the capacity of the soil to function and the degree of expression of this functionality in relation to a given use*" [2.38]; or to "*function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation*" [2.39].

From an agronomic point of view, many factors influence soil quality in terms of physical, chemical, and biological fertility. Each of these relates to specific indicators levels, which are:

• for physical characteristics: the particle size, structure, mass, and humidity, on which depend other parameters such as porosity, softness, specific gravity, toughness, crackability, cohesion, adhesion, plasticity, aeration state, specific heat, and thermal conductivity;

• the chemical and chemical-physical characteristics mainly depend on the fine earth composition, pH, and redox potential;

• the biological characteristics are a function of microbial pools that influence the processes of organic matter humification, mineralization, nitrification, atmospheric nitrogen fixation, etc.

In the qualitative assessment of soil's agronomic vocation for crops cultivation, other two significant factors are the slope and exposure: lying refers to the inclination of the surface to the horizontal plane, which conditions water regimentation, machinery accessibility for cultivation, crop choice, yield, and production costs; while the exposure refers to the orientation of the soil surface to the cardinal points, which is more significant for slope soils, affected by the climatic environment in terms of insolation and wind exposure.

2.6. Soil Skeleton

The rock fragments or coarse fraction of soil with a diameter over 2 mm, up to those having a horizontal dimension less than the size of a pedon [2.1], constitute the soil skeleton.

As intensive agriculture is predominantly interested in fine-and the medium-textured active layer of soils, in determining the texture, soil fractions over 2 mm of diameter (gravel and stones) are usually excluded because they are considered as an inert fraction in soil-crops dynamics. However, the skeleton can play a significant role in soil physical and chemical properties, such as water retention and flow, structure improvement, protection against compaction and erosion, thermal regulation, and bulk density. In some cases, the skeleton also shows chemical properties similar to or higher than those of the fine earth. It may contribute in weathering events involving the dissolution of carbonates and forming secondary minerals with the subsequent creation of voids. It also may release nutrient cations and render the most weathered clasts like fine earth.

Therefore, it plays a significant role as a reservoir of nutrients, as a source of effective cation exchange capacity (ECEC), and as adsorber of organic pollutants, also with favourable effects on plant growth [2.40 - 2.43].

On the other hand, an excessive presence of skeleton in the soil's arable layers hinders or is incompatible with the operational requirements of modern cultivation techniques and pieces of machinery (e.g., minimal tillage, precision sowing), which require fields without obstructions and arable layers of fine heart, as soil coarser fragments easily impede or damage them [2.44 - 2.46].

2.7. Soil Stoniness Assessment

The coarse fraction of the soil's arable layer has been variously defined in terms of skeleton classes percentage by weight, size, surface coverage, volume [2.47 - 2.51]; or through dimensionless indexes such as: Stoniness Degree (Equation (3)), Crushing Degree (Equation (4)), Stoniness Index (Equation (5)):

$$\mathrm{SD} = \mathrm{StM/SoM} \tag{3}$$

$$\mathrm{CD} = \frac{\sum_{i=0}^{5} n_i \cdot StMi}{SoM} \tag{4}$$

$$\mathrm{SI} = \mathrm{SD/CD} \tag{5}$$

where StM = Stones Mass; SoM = Soil Mass; *i* and *n* index as per Table 2.2 [2.52].

Table 2.2. Stone classes indexes.

***i* value**	**Stone Size (mm)**	***n* value**
0	< 2	1.0
1	2÷20	0.8
2	20÷50	0.6
3	50÷150	0.4
4	150÷400	0.2
5	> 400	0.0

In the most advanced farming management types, the maximization of cultivation results, in terms of crop yield, machinery efficiencies, and reduction of operative costs, depends directly on topsoil quality, as defined above; in soils with significant quantities of coarse fractions or stones of the greatest classes in the arable layer, the assessment of soil quality shall also include the influence of skeleton.

Depending on the nature of the parent material, the soil skeleton is highly heterogeneous in terms of lithology and degrees of alteration, which also influences the systems and techniques of soil reclamation: e.g., in the presence of stones of high hardness, it is preferable to resort to the removal of the skeleton, rather than to the on-site crushing; as well as in the case of materials that can worsen, if pulverized, the chemical-physical characteristics of the soil [2.53].

Even though the stones reclamation of agricultural land is an expensive process, the excessive stoniness of the arable layer of agricultural soils entails an interference with cultivation needs, in particular when adopting modern cultivation techniques (e.g., precision farming), and machines for soil cultivations (e.g., tilling, seeding, fertilizing); and damage or makes impracticable the use of the machinery.

In these conditions, it becomes necessary to proceed with soil destoning, to recover arable land, and optimize management to save non-renewable resources and maximize cultivation results, both in the least developed countries and those with greater availability of machinery and technologies [2.43-2.46].

The Disturbance Degree (DD) calculation evaluates the stoniness impact on the efficiency and operational capabilities of soil tilling and cultivation machines. The DD directly relates to the skeleton, size of the stones, and their size classes distribution as per Equation (6)

$$DD = 0\times X + 10\times Y^5 + 10\times Z^2 + 10\times U^{0.9} + 10\times W^{0.5} \qquad (6)$$

where X, Y, Z, U, W, indicate the proportions, expressed in unit terms, of the different particle size classes, the sum of which must always be equal to 1 (100%).

Of these, the X class, corresponding to the fine earth, always has zero value; Y class (gravel, fine & medium gravel: 2-20 mm) does not represent an impediment to soil tillage's; the Z class (gravel, coarse gravel; medium stone: 20 -50 mm), at about 40%-50% affects the operational capabilities of the PTO moved machines; the U class (cobble, large stones: 50-150 mm), sets significant limits for machining already from 15%-30%; the W class (stones, huge stones: >150 mm), involves severe problems of soil tillage's management already at the 10% of presence [2.54].

2.8. Soil Destoning Systems

The choice of a better reclamation method depends on environmental and managerial factors, such as soil structure, percent, typologies and size of the stones, crop needs, machinery availability. The most used destoning systems in agricultural lands are basically three: the stones collection and removal from the field, the on-site stones crushing, and the stones burial [2.55 - 2.59].

2.8.1. Stone Removal

The stones removal usually consists in a three-step process: collection, transportation, disposal. The objective of these operations is the removal of stones that reduce the efficiency of the cultivation machines. The simplest approach in stony soils reclamation is to gather the stones from the surface of the field using various kinds of machineries, usually pulled and PTO powered (Figures 2.3 a)-d)) for picking and loading the stones.

Large stones intermixed with the soil or entirely below the surface of the ground require a deep plowing for breaking the soil (Figure 2.4) [2.60] before their removal or, in the case of boulders, the use of a rock digger (Figure 2.5) [2.61].

Figure 2.3. Samples of: (a) Stone windrower; (b) Stone picker; (c) Stone windrower & picker; (d) Stone collector with conveyor belt.


Figure 2.4. Three point carried Ripper


Figure 2.5. Rock digger

In the case of boulders too large to be dug out and drawn off, there are two options available besides leaving them in the field: dig a deep hole next to a boulder and tip into it or split the boulder into smaller pieces to make them easily transportable. This kind of stone removal usually must be repeated for several years to reach a good level of stones reclamation.

The main negative aspects of stone removal from the soil are the reduction of topsoil volume and the lowering of the field plan (proportionally to the removed stones) plus the costs for the preventive soil preparation (ripping, stones windrowing), and the handling and disposal of the removed stones. In addition, the reduction of topsoil volume and the lowering of the field plan may cause the resurfacing of another skeleton, which makes it necessary to repeat the stone reclamation in case the soil tillage is more profound than the reclaimed layer. Although, in some tropical agricultural environments, stones recovered from soil reclamation are used in the construction of stone bounds both for the regulation of water runoff in case of heavy rains in years with high rainfall, and in years of drought, to increase the retention and infiltration of rainwater into the soil, and the amount of water available to plants [2.58, 2.62].

Another stone reclamation system uses a particular type of stone gatherer that works in previously ridge-till arranged soils whose width corresponds to the machine's working width, that collects, sieves, and unloads the fine earth in the reclaimed ridge-till row. In contrast, the stones are kept and taken to a rear conveyor belt that unloads them in lateral windrows corresponding to the carriageways of machines used in cultivation operations (Figure 2.6) [2.63].

Figure 2.6. Stone separator for windrowed soil.

2.8.2. On-Site Stone Crushing

The on-site crushing of stones is adopted on cultivated stony land to improve soil structural characteristics and workability or on uncultivated soils to recover lands for agricultural use, forming an active functional layer for cultivation operations.

Deep soil scarification or plowing usually precedes the crushing of stones to crack and crumble rocky banks, bring buried stones to the surface, and optimize the operative capabilities of machinery; in the case of large boulders, also pneumatic or hydraulic hammers can be used.

The stone crushing in sandy and siliceous soils involves rapid wear of the crushing hammers, so it is usually adopted in more friable (calcareous) soils and with a high degree of stoniness to avoid contact with the fine earth and enhance the crushing efficacy.

For these operations, various typologies of stone crushing machines are available, brought and PTO moved, or towed and self-engine powered, that can directly crush the stones on the ground or act on previously collected and windrowed stones.

The stone crushers all operate with the same principle: a rotating horizontal axle with different peripheral kinds of wear-resistant hammers (e.g., with teeth for calcareous rocks or hammers for granite stones) that impacts with stones, causing their crushing (Figure 2.7).

Figure 2.7. a) Stone crusher with teeth for calcareous rocks and b) with hammers for granite rocks.

Larger stone crushers can work to a depth of up to 400 -500 mm; however, the specific energy consumption (as energy per cubic meter of crushed soil) increases considerably as the depth increases, so it is often of better convenience to keep the crushing not over 150÷200 mm of deep and repeat the operation several times. Also, the choice of better machines for stone crushing depends on several factors such as the soil nature, the level of stoniness, the stones typologies, the surface extension, and what kind of soil one wants to get [2.64 - 2.67].

In addition to high costs and low effectiveness in the case of granite stones (Figure 2.8a), the disadvantage of on-site stone crushing consists of modifying the composition of the soil, with adverse effects on its physical, chemical, and biological characteristics (Figure 2.8 b). Such soil deterioration often requires corrective actions for the subsequent years [2.41, 2.42]. Moreover, if not properly planned and executed, it can also lead to environmental disasters [2.67].

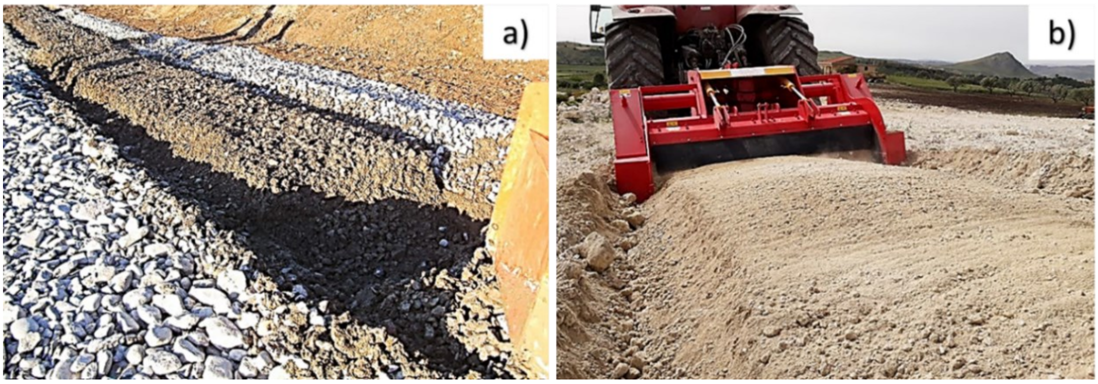

Figure 2.8. a) Crushing efficiency on granite rocks; b) Stone crusher on calcareous rocks.

2.8.3. Stone Burial

An alternative method to removal and on-site stone crushing consists of the skeleton's burial to obtain an arable layer of only fine earth. Starting from the late 1700 s, farmers in Great Britain and the United States started to bury soil skeleton and use it as field drainage when reclaiming lands too wet for ordinary cultivation and improve soil structural conditions and crop yields. Among several different designs proposed for drains, one of them involved digging a ditch and filling it with stones up to 300 ÷ 450 mm from the surface, then filling the last 300÷450 mm of the ditch with fine earth to form the arable layer (plow zone) of the field [2.55].

Several machines that separate and bury the skeleton using continuous soil sieving are available. Such machines commonly derive from horizontal rotary soil milling machines, equipped with a counter-rotating rotor, with a variable number of squared profile blades and a rear-mounted grid, to retain the skeleton inside the carter. They afterward release it on the bottom of the dug layer and cover it with the fine earth ejected through the screening grid as the machine advances (Figure 2.9).

These stone buriers machines are designed to prepare soil seedbeds, usually in horticultural cropping. However, they also bury stones, clods, and crop residues, even in uncultivated lands, to constitute a superficial layer of fine earth whose thickness depends on the working deep and the stoniness of the soil. They form a drainage layer contextually, avoiding the formation of the hardpan layer and water stagnation risks, as occurs in the seedbed preparation with the rotary tiller machines [2.68-2.70].

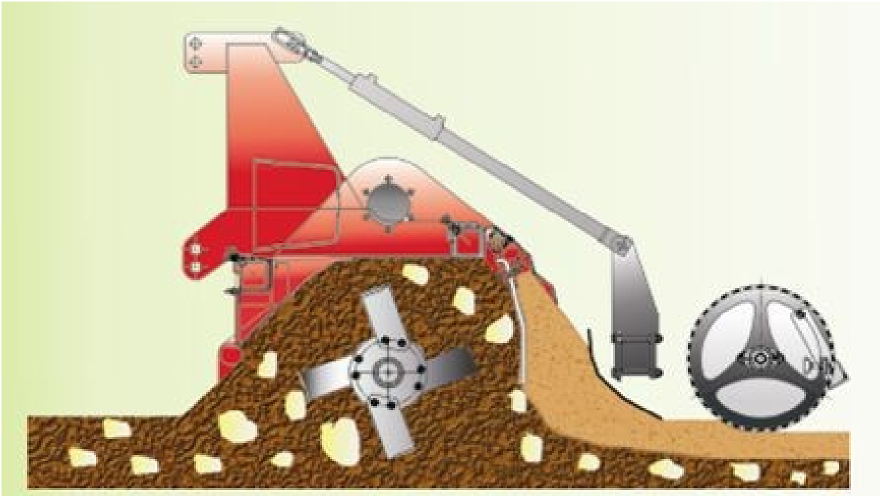

Figure 2.9. Stone burier draft

When adequate conditions exist, this kind of soil skeleton burial allows to obtain a fine earth seedbed, without reducing the topsoil volume and field plan level, as in the case of stone removal, nor modifying the physio-chemical characteristics of the soil, as can occur in stone crushing.

The main drawback of such machines is their low working depth, generally not over 300 mm, limiting their range of action to the seedbed preparation in soils without excessive stoniness or large stones.

A more expensive but long-term stony soil reclamation system, useful in cases of high soil stoniness/stones class, consists of burying the skeleton beyond the tillage depth, thus obtaining the desired arable layer of fine earth only. The operation can be done for the whole field, or only for the field zones with a Stone Index or Disturbance Degree higher than those bearable by machines needed in soil cultivation. This technique consists of digging trenches of depth-dependent on the percentages and size classes of the skeleton and the desired depth of the fine earth layer. Then, the excavated soil is sieved to discharge the separated stones to form a draining layer at the bottom of the trenches and cover them with the sieved fine earth remaining fractions to form the new active (arable) layer. Given the lack of specific machinery, it is possible to proceed with industrial earth-moving machines to carry out this type of reclamation of stony soils, providing them with proper modifications of the conveyor belts and the drainage path to stratify the sieved fractions in the expected order (Figure 2.10) [2.71].

Figure 2.10. Self-moving industrial trencher.

2.9. Conclusions

Suitable soil management is a key factor for successful farming process in any cropping system, both traditional or extensive, and, more significantly, in modern site-specific agricultural management. In the current conditions of soil use due to the expansion of urban and industrial activities and the increase of soil degradation and desertification processes, in the absence of realistic possibilities to reverse this trend in the short term, it is of primary importance to maximize the efficiency of agricultural management. Since the usability of different agricultural techniques is strictly dependent on soil quality, managing this last for machinery and cultivation is the first parameter for cropping success.

This fact primarily depends on the farmer's ability to choose the most effective cultivation management for optimizing the active soil layer's physical, chemical, and biological fertility, reducing the production costs, and enhancing the environmental sustainability of agro-industrial lands; at the same time limiting the overexploitation and degradative phenomena of the non-renewable resource "soil".

Among the factors that most influence the cultivation results, in terms of crop yield, machinery efficiency and reduction of operating costs, the presence of soil skeleton is of particular importance: depending on the quantities and dimension of stones present in the arable soil layer, coarse gravel and medium stone (20-50 mm), reduce the operational capabilities of the PTO driven machines from about 40% to 50%; cobble and large stones (50-150 mm) set significant limits for machining already from 15% -30% of presence; stones and huge stones (>150 mm) involves severe problems of soil tillage's management already at the 10% of presence.

Although the stones reclamation of agricultural land is an expensive process, if the skeleton amount exceeds the Disturbance Degree (DD) acceptable by machinery, it becomes necessary to proceed with destoning. The most used stones reclamation systems in agricultural lands are the stones collection and removal from the field, the on-site stones crushing and the stones burial.

The choice of the best method involves organizational factors, such as soil structure, the nature of the stone material, i.e., hardness, the DD of the skeleton, as the size of the stones, size classes distribution, and volume percent, and crop needs and machinery availability.

The state-of-the-art about the reclamation methods of stony soils highlights the availability of various technologies and machinery designed and usable in different working conditions, according to specific environmental conditions and cultivation needs. Given the operational needs of agro-industrial crops and the diffusion of precision farming techniques, it is of particular importance to operate on arable layers composed of fine earth only, or with a skeleton content compatible with cultivation machines. This is the discriminant factor in the coarse fractions management, also taking into account the possible negative effects of the various stones reclamation methods, such as the lowering of the field plan, in the case of the stones removal, or the modification of the chemical-physical characteristics of the soil, in the case of on-site crushing; while the stone burial under the arable layer could be a more effective reclamation system in the long term, without the drawbacks of the two others mentioned systems.

An economic analysis should be conducted in the choice of the better reclamation method, e.g., concerning removal, the economic value of the stones could be considered because companies operating destoning operate in road pavement or building sectors as well and may have an interest in the removed material. However, it is necessary to pay attention to the regulatory framework of each country because stone removal and reuse may fall among the non-agricultural production activities or be considered a borderline activity between soil reclamation and mining, like quarry works. Such aspects require specific regulatory studies that go beyond the scope of this review.

The specificity and costs of the machines and yards for the different methods of reclamation entail their availability for service contractors or large farms. The development of suitable machines for each reclamation method can result from the levels of interest and convenience in the implementation of advanced cultivation methods, which mainly require optimized soils for boosting machineries efficiency.

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3. Soils Characteristics in the Experimental site

The project idea originates from the assessment of the high stoniness state of most soils in the territory, which insist on the limits between the high gravel plain and the river valleys of the Holocene waterways in which the Treviglio's countryside lies (Figure 3.1), as described by the ERSAF [3.1].

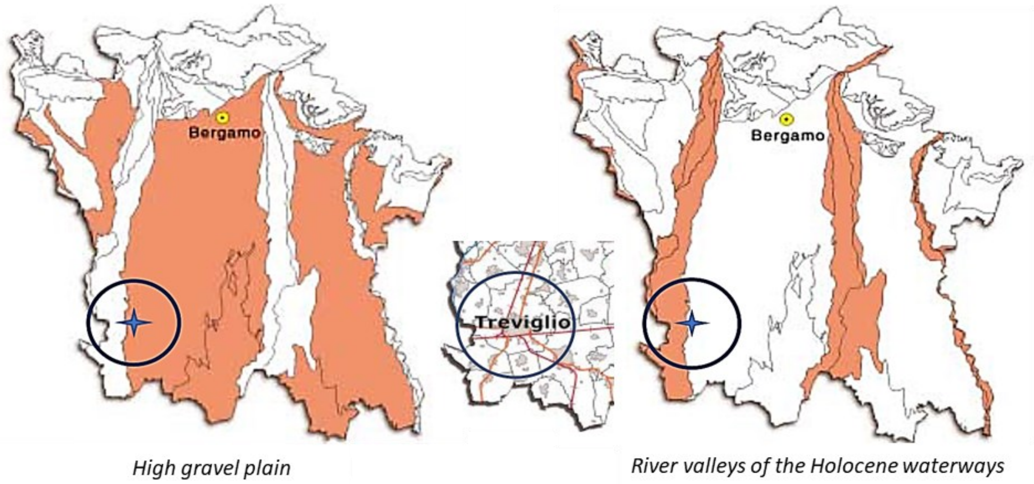

Figure 3.1. ERSAF, 2004. Soils and landscapes of Bergamo's province

In the experimental research center of CREA-IT in Treviglio (Bergamo's province, Lombardy), the soils have a stoniness with varying degrees of hardness, from limestone to crystalline shale and quartzites of hardness from 3 to 7 degrees Mohs, with "B" workability class, and Disturbance Degree between 3.2 and 5 [3.2].

At the end of the 1990s, some experimental reclamation activities were carried out on these soils according to the classic stone removal and on-site crushing methods [3.3]. However, these methods have intrinsic limitations and inefficiencies that limit their effectiveness in the long term (low operating depth, reduction of topsoil volume, stones resurfacing after soil tillage's, stones hardness), solving the cultivation problems only partially and in the short-term, of using most modern techniques and machines of precision agriculture, in particular the seeders.

From this consideration came the idea of using a reclamation method of greater long-term effectiveness, for the constitution of an arable layer more compatible with the functionality and efficiency of the cultivation machines, in terms of lower Disturbance Degree, and the crop needs, for the higher fine earth percentage in the cultivation layer.

3.1. Geoelectric Characterization of Experimental site soils

For the determination of the farm topsoil's characteristics, a geoelectric analyses was carried out and, with the application of a classification algorithm based on the resistivity values relative to the soil layer 0-1 m, a three homogeneous macro-areas zoning was obtained, based on the electrical response (Figure 3.2) [3.4].

Figure 3.2. The shape of the homogeneous geoelectric soil zones.

Profile No. 4 is representative of soil class "A", consisting of soils with a depth of about 600 mm with a medium sandy texture, characterized by a surface layer of about 200 mm of dark-brown color, with skeleton (25 - 35%) consisting of pebbles and gravels, of moderate subangular polyhedric, fine and medium structure and with fine pores. On the surface, there is a relatively abundant presence of pebbles. From a depth between 200 mm to about 600 mm, there is a brown-color layer, with abundant medium and large skeleton (50 - 60%) with weak fine subangular polyhedric structure and fine and medium pores. At depths over 600 mm, the skeleton is very abundant (>70%), consisting of pebbles and gravel.

Profile No. 1 represents soil class "C", with soils with a depth of about 1000 mm, medium to silty texture, characterized by a surface layer of about 200 mm of dark-brown color, with 10 - 15% skeleton consisting of small and medium gravel; fine and medium polyhedric structure; and abundant fine pores. From 200 to about 700÷800 mm deep, there is a brown/olive-brown layer with a frequent (25 - 35%) medium and large skeleton. It has medium and large angular polyhedric structures and fine pores. Over 700÷800 mm deep the skeleton is abundant (35 - 50%), consisting of pebbles and gravel (Figure 3.3).

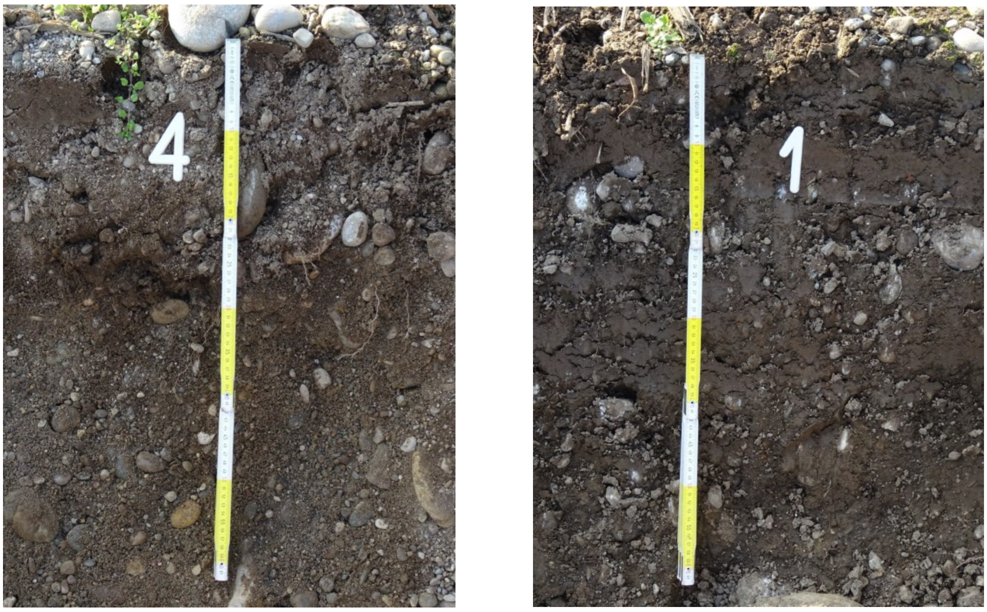

Figure 3.3. Samples of geoelectric zones soil profiles (the numbers refer to the homogeneous geoelectric soil zones identified)

The undisturbed (control) parcels mainly insist on type "A" (profile 4, P4 plot) and partly "C", (profile 1, P2 plot), (Figure 3.4).

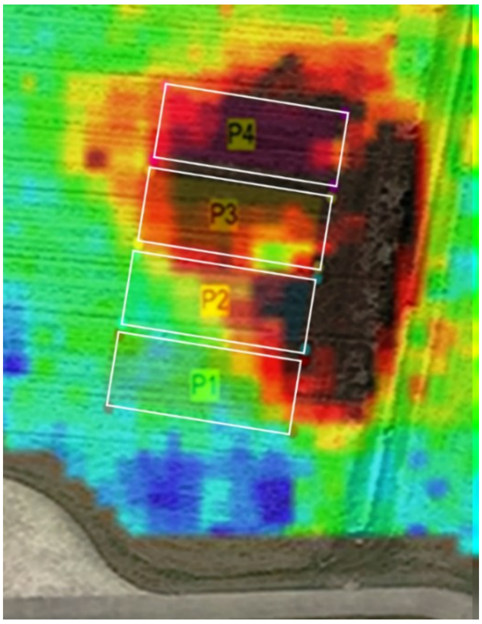

Figure 3.4. Experimental plots on soil geoelectric profiles (0-1 m deep): P1, P3 reclaimed plots; P2, P4, undisturbed control plots.

The reclaimed parcels (P1, P3) are constituted of a draining layer of about 40 cm, formed by the screened stones, and an arable layer of fine earth, including the skeleton up to 40 mm of diameter, of about 600 mm, as detailed in the following chapter.

3.2. References

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4. Deep burial reclamation activities

The original project aimed to implement and validate a reclamation method of agricultural stony soils as alternative to the common stone removal or on-site stones crushing techniques. The planned activities will be carried out through a first phase of prototyping and optimization of an operating machine able to carry out the reclamation of the soil, through in-continuous excavation, screening and stratification of soil fractions with the coarser ones in depth, such as a draining bed, and the fine earth to form an arable layer of thickness adequate to the needs of the crop; at the same time solving the cultivation problems of stony soils in the long term.

Currently, there are some machines that operate with this method, but with little operating depth [2.68 - 2.70].

The goals of the planned activities aimed also at the agro-economic validation of the reclamation method proposed, also according to Precision Farming techniques that may be implemented for crop results maximization.

For this purpose, a small-scale prototype was designed and assembled (Figure 4.1), for which an industrial invention, Patent number: 102017000013866 of 08/02/2017, was claimed; the patent was rejected for lacking novelty as some of its claims already existed in other documents on file, not detected during the prior art search.

To validate the effectiveness of the screening and stratification method devised, the prototype was subject to sieving tests (Figure 4.2 a, b). As expected, the different stones classes, divided according to the number and size of the meshes of the screens, fall in sequence on the front of the machine, and are covered by the fine earth that crosses through the sieves, as they move forward.

An industrial partnership was sought for the engineering of a real-scale machine, with the idea of upgrading an existing trencher machine (Figure 4.3) to which it was assumed to combine a sieve that operated in series; while the results of lab scale tests were presented at the Agralia event in Sora (Frosinone, Italy), (Figure 4.4).

The lack of common goals in the partnership did not allow to carry out the planned activities; then a discontinuous yard was prepared for the validation of a field-scale reclamation method, as detailed below.

Figure 4.1. The prototype of sieving machine realized.

Figure 4.2. Soil screening tests performed at CREA-IT Research Centre with local samples of soil: a) static test; b) dynamic test.

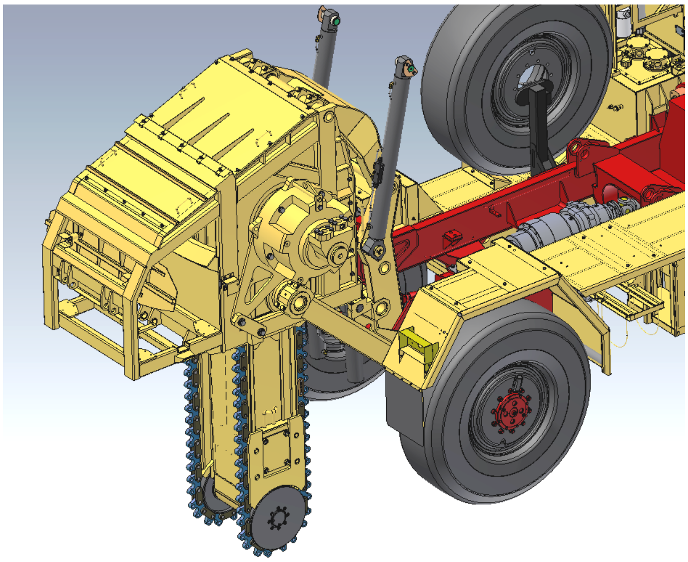

Figure 4.3. The trencher draft (source Tesmec)

Figure 4.4. Poster of Prototype Screening tests presented to Agralia 2017 event.

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Article

Assessment of a Deep Burial Destoning System of Agrarian Soils Alternative to the Stone Removal and On-Site Crushing

Pietro Toscano, Maurizio Cutini, Giovanni Cabassi, Nicolò Pricca, Elio Romano and Carlo Bisaglia

Abstract: Among its many functions, soil represents the active natural medium for plant growth. Different soils have various structural characteristics, that correspond to their qualitative parameters in terms of physical, chemical, and biological fertility. Because of their extremely slow formation processes, soils are also a non-renewable resource, easily subject to degradative processes. Among their mineral constituents many agrarian soils present, in addition to the fine earth, variable percentages of coarse fractions in their arable layer, which interfere with the crop growth, requiring more energy to manage cultivation operations, and damaging the machinery up to making its use impractical. In these conditions, it becomes necessary to proceed with the soil destoning, particularly for the management of Precision Farming techniques. Depending on the percentages, sizes and types of coarse fractions, the soil destoning systems concern: (i) the collection and removal of stones from the field, (ii) the on-site stones crushing, and (iii) the stone burial. In this article, we report the first evaluation of a deep burial destoning system carried out in the CREA Experimental Centre of Treviglio (Bergamo, Italy). With the described reclamation system, a significant long-term improvement of soil quality in a 600 mm thick arable layer was achieved; avoiding the shortcomings of the destoning systems as commonly applied in agricultural lands.

Keywords: soil quality; stoniness; soil destoning systems; precision farming

5.1. Introduction

In the common meaning, the word "soil" defines the top layer of the earth's crust, composed of mineral particles, organic matter, water, and air, that hosts most of the biosphere and constitute the natural medium for the growth of plants [5.1, 5.2].

In the agricultural context, the concept of "soil quality" [5.3] is associated with those of productivity and sustainability of use and is evaluated in terms of physical, chemical, and biological fertility, variously defined as the soil capability to "*receive, store and recycle water, minerals and energy to support plant production at optimal levels and preserve the health of the environment*" [5.4]; or to "*act as a natural means for the growth of plants that sustain human and animal life*" [5.5]; or the "*capacity to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation*" [5.6].

Because of their extremely slow rate of forming processes, soil must be considered as a non-renewable resource and highly susceptible to degradative processes and threats, such as erosion, mineralization of organic matter, destructuration, lack of biodiversity, floods, and landslides.

Various combinations or intensities of these threats lead to the fertility reduction of soil and enhance the desertification phenomena [5.7]. To these must be added the soil consumption due to the artificial covers: in the years 2012–2018, land consumption in Europe amounted to 539,000 hectares/year, 78% of which by agricultural areas [5.8]; while in Italy the artificial coverage reaches 7.11% of the national territory, corresponding to about 2,140,000 hectares, mainly represented by herbaceous areas, with an estimated increase of 5,670 hectares in the land consumption in 2020 compared to 2019, corresponding to an average of over 15 hectares per day [5.9 – 5.12].

In absence of realistic possibilities to reverse this trend in the short term, it becomes fundamental to maximize the efficiency of agricultural practices, adopting all cultural techniques compatible with the concepts of sustainable intensification to enhance crop productivity, contextually limiting the soil exploitation and degradative phenomena. This leads firstly to maximize the efficiency of the use of resources, according to the concepts of marginal productivity pursuit in the use of production factors since, in the absence of real economic profitability, no environmental practice can be effectively adopted [5.13 – 5.15].

In agricultural management, the most important factor in the implementation of the different cultivation methods and in the consequent cultivation results, is the soil texture, as the distribution of the mineral particles class size that constitutes the fine earth of their solid fraction; these last are sand (0.05 to 2 mm), silt (0.002 to 0.05 mm), and clay (less than 0.002 mm), that define the different types of soil according to their respective texture class percentages [5.16].

In the determination of texture, soil fractions over 2 mm of diameter, such as pebbles, cobbles, gravel, stones, and boulders, are not included in the textural classes and are considered as a relatively inert fraction in soil and crops dynamics.

However, the soil skeleton can have some significant physio-chemical properties that affect soil structural characteristics, such as water flow and retention, compaction and erosion, thermal exchange, and bulk density [5.17, 5.18], showing in some cases properties similar or higher than the fine earth in the formation of secondary minerals, thus playing a significant role in the soil physio-chemical dynamics as a reservoir of nutrients, cation exchange capacity (ECEC) and adsorption of organic pollutants [5.19 – 5.21]. On the other hand, an excessive presence of skeleton in the soil's arable layers hinders or is incompatible with the operational requirements of modern cultivation techniques and machinery (i.e., minimal tillage, precision sowing), which require fields without obstructions and arable layers of fine heart, being easily impeded or damaged by coarser fragments [5.22 – 5.24].

With the aim to contribute to solving the stoniness problems of agrarian lands, avoiding the shortcoming of destoning systems commonly adopted, an experimental trial of stone deep burying has been performed, to enhance in long-term the soil workability, increase the thickness of the arable layer, and maximize the operativity of cultivation machines.

5.2. State of the Art

5.2.1. The Soil Skeleton and Stony Soils Workability Classes Concept

The presence of stony soils in agrarian lands is estimated in about 30% in Western Europe (Figure 5.1) [5.25]; more than 60% in the Mediterranean basin; and about 16% in the USA [5.21].

The coarse fraction in the soil's arable layer is commonly described in terms of skeleton percentage by weight, surface coverage, and size of the fragments, as per Table 5.1 [5.26]. Other classifications are based on stoniness percentages by volume [5.27], or through dimensionless indexes, such as the Stoniness Degree, defined as the ratio between the Stones Mass (StM) and Soil Mass (SoM) (1) [5.22]:

$$SD = StM/SoM \quad (1)$$

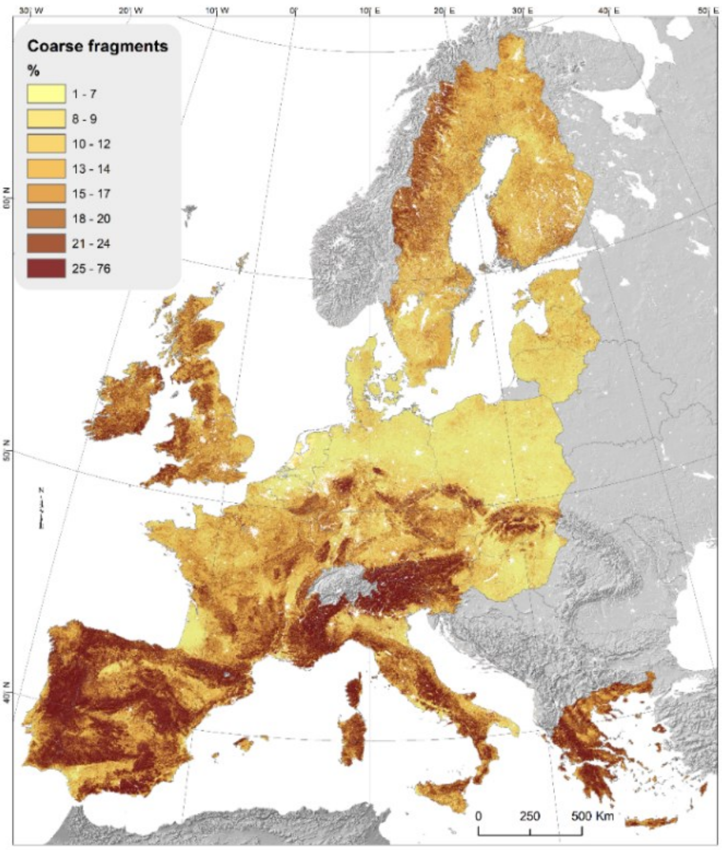

Figure 5.1. Stony soils distribution in Western Europe [5.25].

Table 5.1. FAO Classification of coarse surface fragments.

Surface Cover	(%)	Size Classes	mm
N: None	0	F: Fine gravel	2–6
V: Very few	0–2	M: Medium gravel	6–20
F: Few	2–5	C: Coarse gravel	20–60
C: Common	5–15	S: Stones	60–200
M: Many	15–40	B: Boulders	200–600
A: Abundant	40–80	L: Large boulders	600–2000
D: Dominant	>80		

The stoniness impact on the efficiency and operational capabilities of soil tilling and cultivation machines can be evaluated through the calculation of the Disturbance Degree (DD) that is directly proportional to the amount of skeleton, the size of the stones and the distribution of their size classes, as defined by the formula (2) [5.28]:

$$DD = 0\times X + 10\times Y^{5} + 10\times Z^{2} + 10\times U^{0.9} + 10\times W^{0.5} \qquad (2)$$

Where X, Y, Z, U, W, indicate the proportions, expressed in unit terms, of the different particle size classes, (Figure 5.2), the sum of which must always be equal to 1 (100%).

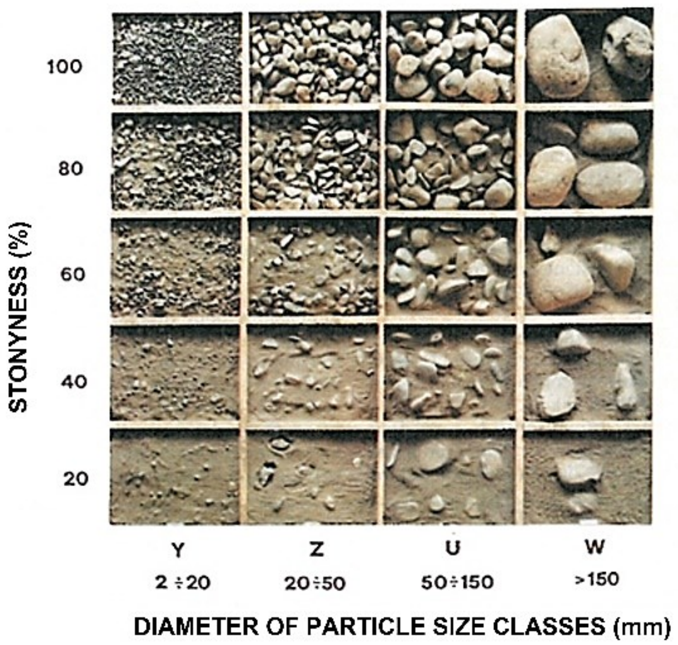

Figure 5.2. Soil samples with different percentages of stones of different classes.

Of these, the X class, corresponding to the fine earth, always has zero value; Y class (gravel, fine & medium gravel: 2÷20 mm) is considered to be of no impediment to soil tillage's; Z class (gravel, coarse gravel; medium stone: 20÷50 mm), at about 40÷50% affects the operational capabilities of the machines, in particular, if moved by the PTO (power take-off); U class (cobble, large stone: 50÷150 mm), becomes significant limiting for machining already from 15÷30%; W class (stone, very large stone: >150 mm), involves serious problems of soil tillage's management already at 10% of presence.

The concept is graphically reported in Figure 5.3, where the 10% of the "W" class line (0.1) corresponds to 3.3 value of Disturbance Degree, which is over the limit of "A" workability class of soil, as represented in Figure 5.4 [5.28].

Based on the different levels of Disturbance Degree, the operative limits of some cultivation machines are reported in Figure 5.4. In the graph, the green zone indicates soils that can be tilled without limitations; the yellow zone, the soils workable with appropriate precautions, to avoid early wear or breakage of the working tools; the red zone, represent soils having stoniness incompatible with an acceptable quality of work and/or the functional integrity of the machinery [5.28].

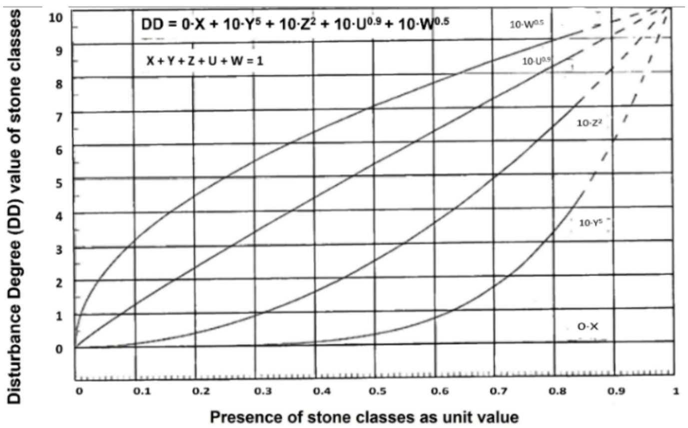

Figure 5.3. Disturbance Degree Curves.

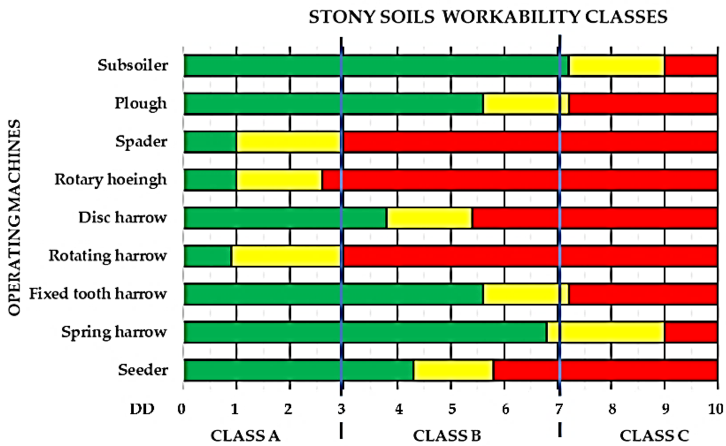

Figure 5.4. Operative limits of some cultivation machines at different DD levels of soils stoniness.

Even though the removal of stones from agricultural land can be an expensive process, the excessive stoniness of arable layer entails interference with cultivation needs, damage to machinery, increase energy consumption in cultural operations, making it difficult or impracticable to use machinery [5.29].

Depending on the type of soil tillage's required by the crops, the identification of the soil workability class based on the stone's disturbance degree (DD), can be a good index for the choice of the machines to be used; as well as induce to the soil destoning, to optimize the soil quality, according to the operational needs of modern cultural techniques, and soil management machines, with the aim of saving non-renewable resources, reducing operating and maintenance costs and maximizing crop yields.

5.2.2. Soil Destoning Systems

The most used destoning systems in agricultural land are basically three: the stones collection and removal from the field, the on-site stones crushing, and the stones burial.

5.2.2.1. Stone Collection and Removal

The clearing of stones from fields usually consists of a three-step process: removal; transportation; disposal [5.30, 5.31]. These steps concern gathering the stones from the surface of the field and placing them in a pile or windrow for stone bund building or later removal [5.32 – 5.34], using various kinds of machinery, usually pulled and PTO moved (Figure 5.5 a–c).

The main negative aspects of soil stone removal are: *i*) the reduction of the topsoil volume, in proportion to the volumes of stones removed; *ii*) the possible resurfacing of other skeletons with subsequent soil tillage, especially if effected at a depth greater than the destoned layer, which makes it necessary to repeat the destoning operations; *iii*) additional costs for the preventive soil preparation (ripping, stones windrowing), the handling and the disposal of the removed stones.

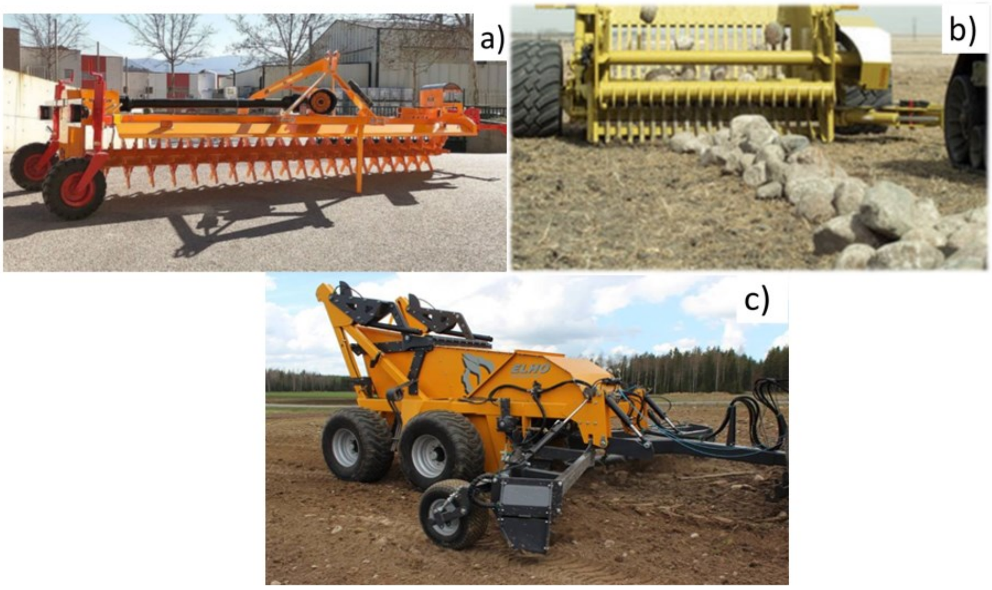

Figure 5.5. a) Stone windrower; **b**) Stone picker on windrowed stones; **c**) Stone windrower & picker.

5.2.2.2. On-Site Stone Crushing

The on-site crushing [5.35, 5.36] is carried out using various kind of stone crushing machines, moved by PTO or self-powered, with different operating capacity, depending on working depth, size, and strength of the stones to be crushed, and equipped with teeth for calcareous rocks (Figure 5.6a) or hammers for granite stones (Figure 5.6b).

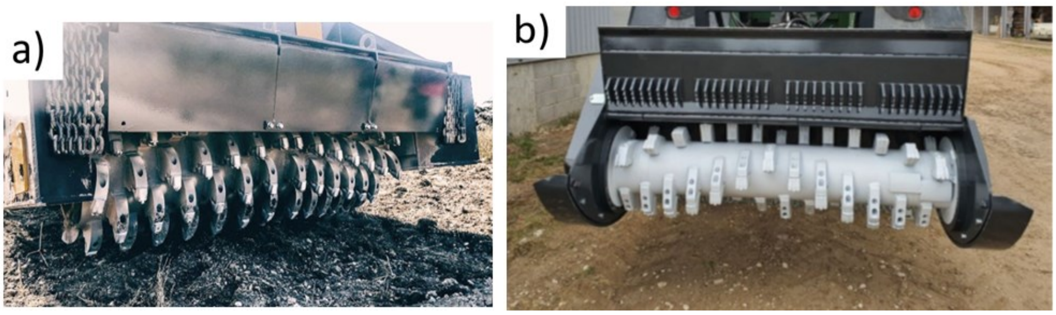

Figure 5.6. Stone crusher with teeth for calcareous rocks (**a**) and hammer for granite rocks (**b**)

The shortcoming of this technique concerns its high costs and poor effectiveness in the case of granite stones, and changes in soil composition, with possible negative effects on its physical, chemical, and biological characteristics [5.21]; moreover, if not adequately planned and carried out, it can be also responsible for environmental disaster [5.37].

5.2.2.3. Stone Burial

The burial of the skeleton below the tillage depth avoids the reduction of topsoil volume, does not change the physio-chemical characteristics of the soil, and allows to obtain an arable layer composed of fine earth only. The typical approach used for burying very large boulders is to dig a hole of adequate depth close to the boulder and then tip it into the hole and cover it with soil [5.30]. For the other, more common, skeleton classes, some machines that carry out the separation and burying the skeleton by continuous soil sieving are currently available: these machines are usually derived by horizontal rotary soil milling machines, equipped with a grid that retain the skeleton which is covered by the fine earth ejected through the grid with the advancement of the machine [5.38]; or soil sieving machines designed for windrowed soils [5.39].

The limit of both these kinds of machines is their working depth, not over 300–400 mm, which makes them inefficient in case of high percentages of skeletons, for the small arable layer of fine earth obtainable, or in presence of large stones (Figure 5.7).

Figure 5.7. Sample of large stone present in the soil sieved by experimental plots.

In this study, a concept of high deep burying was adopted, with the purpose to obtain a long-term stable arable layer of higher workability class, and thickness for the cultivated crops; avoiding the described shortcomings of destoning methods as currently adopted.

5.3. Materials and Methods

The trial has been carried out at the experimental farm in Treviglio, Northern Italy (45°31′14″ N; 9°35′27″ E; +128 m asl), in a soil classified as Calcic Skeletic Mollic Umbrisol, with neutral-sub alkaline pH, according to the IUSS classification [5.40]. In these experimental fields, many surveys have been carried out over the past years to evaluate both some destoning systems [5.29, 5.41, 5.42] and the geoelectric variability of the soils [5.43], with the aim to enhance the qualities of soils and the performances of cultivation machines; and obtain the prescription maps to maximize the production of the crops.

5.3.1. Planning of Experimental Parcels

For the planned experimental activities, in the farm plots a parcel with the presence of skeleton consisting of pebbles, gravels (classes Y–U), and coarse stones (class W) was identified, in percentages ranging from 25÷35% in the 0÷200 mm layer; 50÷60% to 200÷600 mm deep, and >70% over 600 mm deep (Figure 5.8).

Figure 5.8. Soil profile in experimental plots.

For the destoning of the test plots with the method described below, a HYUNDAI Robex 140LCD-7A crawled arm excavator, equipped with a dozer blade, a toothed bucket, and a smooth-blade bucket was used. For soil workability class enhancement, a CM-CBR18 sieving bucket, with 40 mm diameter grid holes was chosen, among those available on the market, accordingly to the reclamation trial needs.

Two test plots of 10 × 20 m area were chosen (P1 and P3, Figure 5.9), as the thesis to carry out the planned stones reclamation, while two other contiguous plots of the same area of undisturbed soil have been delimited as control tests (P2 and P4, Figure 5.9), for the following agro-mechanical soils and machinery comparisons.

In the P1 and P3 plots, the soil was dug up to about 1 m deep (Figure 5.10a). The dug soil was then sieved (Figure 5.10b), from time to time discharging in the trenches the stones retained by the grid (Figure 5.10c).

The stone layer formed at the bottom of the trenches (Figure 5.11) was levelled and compacted with repeated passages of the crawled excavator; then the filling of the trenches with the sieved fine earth, including skeletal fractions up to 40 mm (classes Y and Z) was completed (Figure 5.10d).

To obtain an acceptable consolidation of the fine earth layer, and to limit the possible variations of the field plan due to topsoil settling, the filling was carried out in two phases providing, as for the stone layer, to levelling and compacting both layers of fine earth, with repeated passages of the crawled excavator (Figure 5.10e).

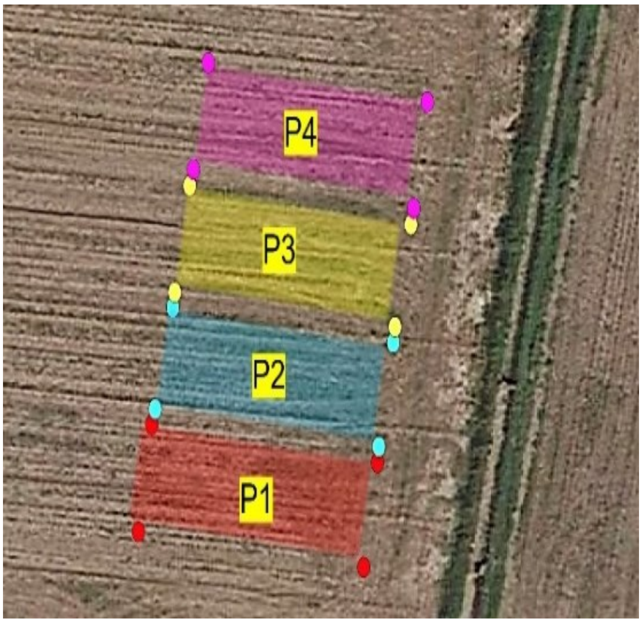

Figure 5.9. Experimental plots: P1, P3 destoned; P2, P4, undisturbed control.

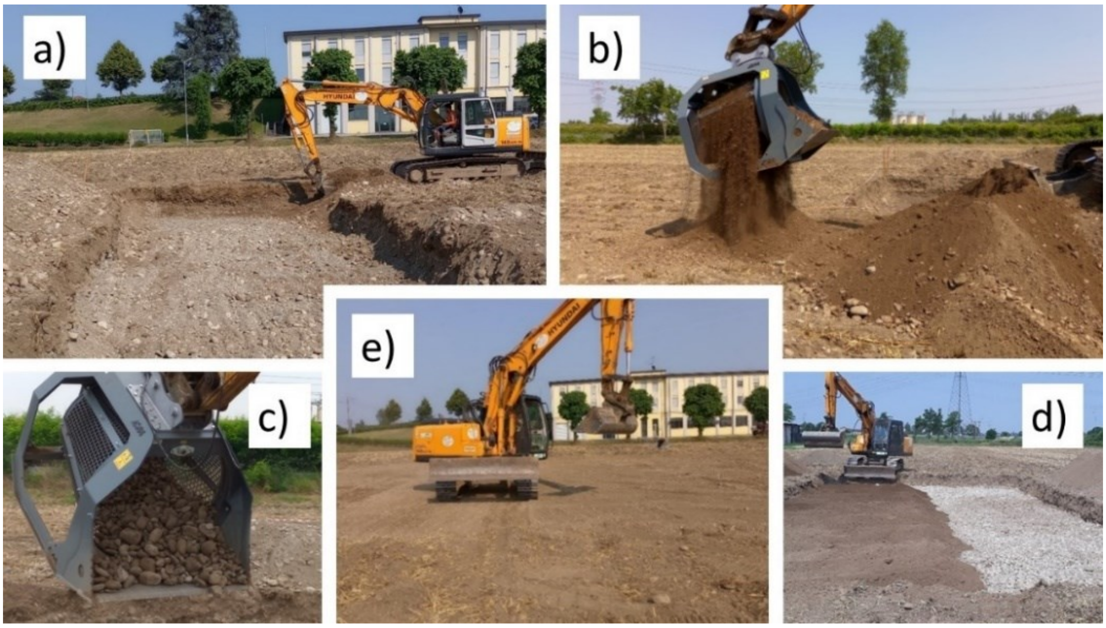

Figure 5.10. Scheme of the processing phase: (**a**) Trenches digging; (**b**) Soil sieving; (**c**) Discharging of retained stones in the trenches; (**d**) Refilling of trenches with sieved fine earth; (**e**) Compaction of sieved fine earth layer.


Figure 5.11. Stone layer at the bottom of trenches.

5.3.2. Electromagnetic Survey

Soil apparent electrical resistivity is an important indicator that relates directly and indirectly to soil properties [5.44 – 5.48]. As it is expected that the burying technique does not change the physio-chemical characteristics of the soil, an electromagnetic investigation was performed through the analysis of electrical conductivity in the test area at four depth layers, using a SoilXplorer (GeoProspector GmbH, Wienersdorfer Str. 20-24, 2514 Traiskirchen, Austria) soil conductivity sensor.

This survey system is based on electromagnetic induction, for which a primary field is created by an emitting coil that induces a secondary field in the soil. Soil inhomogeneity can be measured using receiving coils and converted to different soil parameters by studying appropriate correlations.

In particular, the SoilXplorer sensor consists of a coil that generates an electromagnetic signal, which induces a secondary field in the soil that is measured by four receiving coils placed at different distances from the emitter (Figure 5.12).

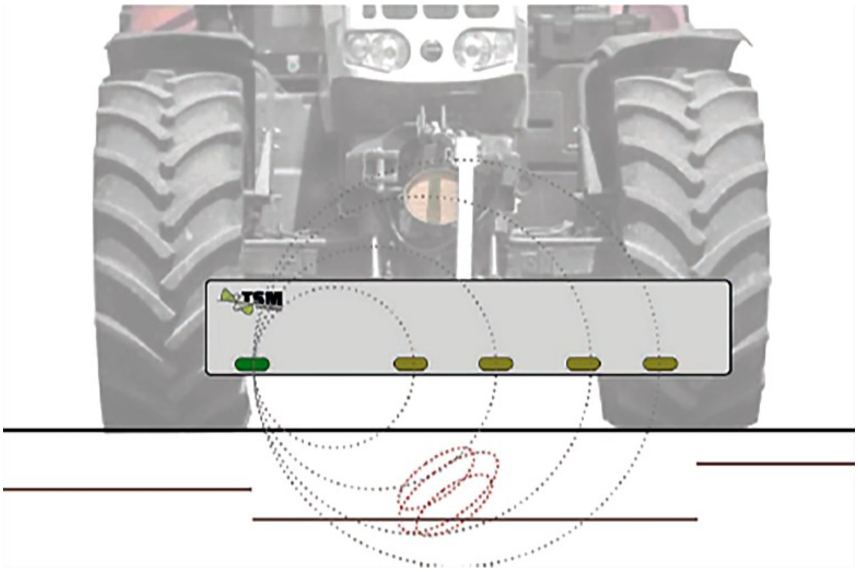

Figure 5.12. SoilXplorer operating schema. The sensor is responsive to electric charge density per unit volume of soil.

Under the same conditions of compaction, tillage and plant residues on the surface, this physical quantity is influenced more by the granulometry than the texture of fine earth in the soil.

Soil conductivity (ECa) at four different depths expressed in milliSiemens per meter (mS/m) is thus measured. When the sensor is 400 mm above the ground, these layers are indicatively: ECa1 = 0÷250 mm, ECa2 = 0÷600 mm, ECa3 = 0÷950 mm, and ECa4 = 0÷1150 mm.

To record and map the soil heterogeneities for each of the four soil layers, the system is equipped with a GNSS receiver to associate the geographic coordinates with recorded electrical conductivity values. All data are managed and recorded by an on-board monitor.

For acquisitions of the data, the sensor was mounted directly on a tractor (Figure 5.13) and equipped with a shielding system such that the electromagnetic field generated is not affected by the metal mass of the tractor. Data acquisition was carried out following a path with a transect of about three meters (Figure 5.14). The acquired data were exported directly from the on-board monitor and processed with QGis open-source software.

Figure 5.13. The SoilXplorer sensor rear-mounted on a tractor.

Figure 5.14. The path recorded during the acquisition of electrical conductivity data.

5.4. Results and discussion

Fewer specific data on effects of soil stoniness reclamation are available in the literature [5.22, 5.28 – 5.32, 5.35 – 5.37], none of them compare with this trial that was carried out with the aim of solving in long-term the highlighted shortcomings of destoning systems as usually applied in agricultural lands.

5.4.1. Arable Layer Soil Quality

With this deep burial stone reclaiming system, an evident modification of the original soil profile composition in terms of soil disturbance degree (DD) and workability class was obtained: starting from a class "B" and DD = 4.15 soil (estimated X = 0.6, Y = 0.1, Z = 0.1, U = 0.15, W = 0.05), it has been obtained an arable layer of about 600 mm (Figure 5.11) of "A" workability class and DD = 0.1 soil (estimated X = 0.8, Y = 0.1, Z = 0.1, U = 0, W = 0), with the U and W stone classes constituting a draining layer of about 400 mm (Figure 5.8; Figure 5.11) below the tillage depth needed for cultivated crops. In addition, this result was obtained without lowering the field plan, as occurred in the case of stones removal that, in our trial condition, would amount to 400 mm; nor the chemical characteristics of fine earth in the constituted arable layer, as in case of stones crushing.

The very low value of the calculated Disturbance Degree in the reclaimed soil, do not give obstacles to the cultivation machines (harrow, seeder), notwithstanding the presence of Y and Z gravel classes, which can instead be considered useful in the preservation of some soil structural characteristics, contributing to the reduction of physical degradation of fine-textured soils; while the few studies on the effects of soil stoniness on plant productivity confirm that the crop response is conditioned by the texture and nutritional properties of the fine earth available for the root systems, which amount, in this sense, depends on the stoniness level of the topsoil [5.15, 5.17, 5.19, 5.21].

5.4.2. Electromagnetic survey

The results of the electrical conductivity survey, related to the ECa2 layer average values for individual plots, do not show significant differences in the data collected (Figure 5.15, Table 5.2).

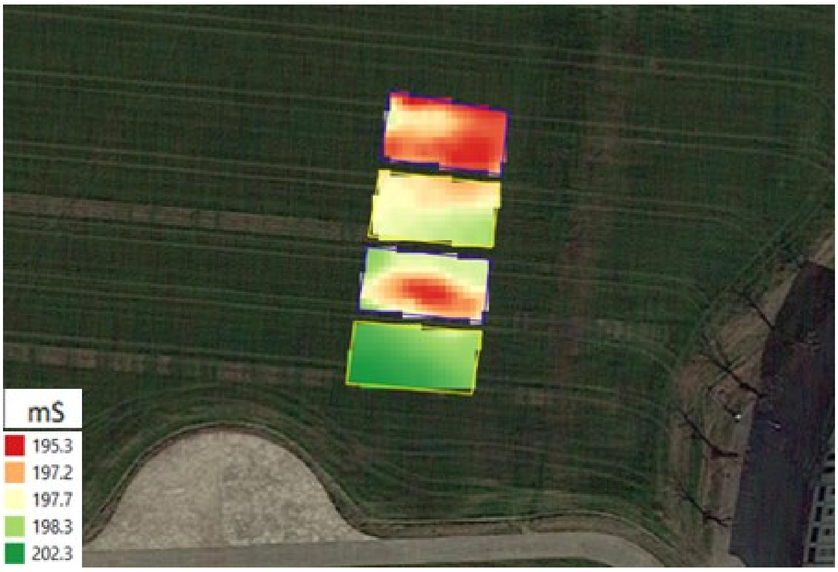

Figure 5.15. ECa2 layer Electrical conductivity values relieved in the trial plots.

Table 5.2. Electrical conductivity average in the trial plots (mS).

Plot	T/C	ECa1 (0–250 mm)	ECa2 (0–600 mm)	ECa3 (0–950 mm)	ECa4 (0–1150 mm)
P1	Thesis	216.5	199.9	192.1	170.7
P2	Control	214.2	197.5	189.7	168.3
P3	Thesis	214.4	197.8	189.8	168.3
P4	Control	213.7	197.0	189.2	167.9

The soil sieving carried out with a 40 mm mesh implies that in the fine earth layer of treated plots a significant percentage of the skeleton is present; moreover, the skeleton fraction larger than 40 mm (U and W stone classes) was not removed from the field but moved on to 600–1000 mm depth layer. Therefore, differences in the electrical characteristics of soils in treated and untreated plots are not detected by the SoilXplorer sensor.

This type and percentage of skeleton present in the 0–600 mm fine earth layer (Y and Z stone classes, estimated to about 20%), do not show appreciable differences in the values of electrical conductivity between destoned (P1, P3) and control (P2, P4) plots, indicating that the change of the layer's stone distribution does not change the soil conductivity.

Even though the results confirmed that on the one hand, the electrical conductivity of the soil remained unaltered, they also showed that to evaluate any differences due to the burial intervention it will be necessary to use different investigation methods, already planned in the next steps of the trial assessment.

5.4.3. Seeding Visual Assessment

After the soil reclamation, at the seeding time, a 24-row pneumatic seeder and a geolocalized drive-assisted tractor were used for the planned winter crop (triticale). As a result, there were observed enhancements in precision and uniformity of seeds planting in the reclaimed plots in comparison to untreated soil (i.e., Figure 5.16 a, b: CREA facility geolocalized sowing trials; unpublished data).

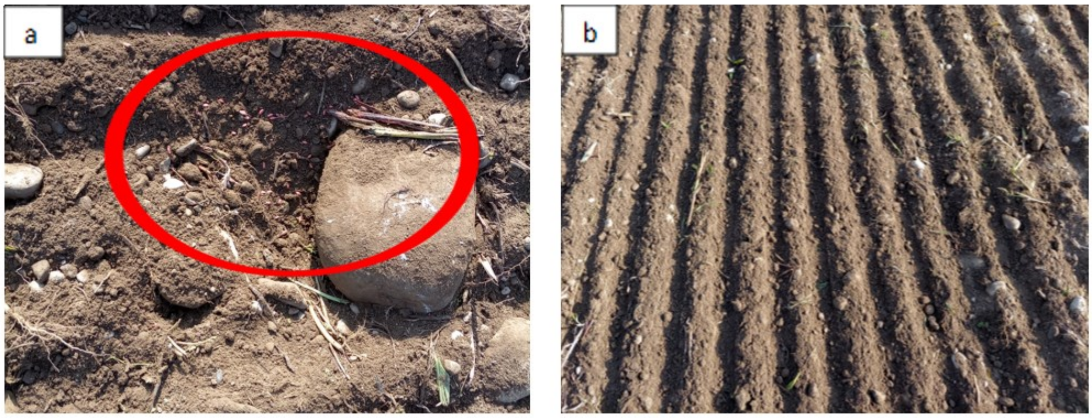

Figure 5.16. Visual sample of precision and uniformity of seeds planting in undestoned (**a**) with, in red box, a sample of unburied seeds; and destoned (**b**) test plots.

5.4.4. Economic Evaluation of the Experimental Trial

With the used machinery, the deep burial operations of U and W stone classes, such as excavation, sieving, refilling, and compaction, of the approximately 400 cubic meters of soil (2 × 10 × 20 × 1 m), required a total of about 24 h of machine work, and consumption of about 400 L of diesel fuel, and a total amount of cost of used yard corresponding to about 150.000 €/ha. This cost is not feasible for field reclamation, but the noticeable long-term amelioration of arable layer obtained with this technique will lead to evaluations on the perspective of engineering a machine able to carry out automatically and continuously the described deep burial destoning system, to make it economically sustainable for most of the stony lands.

5.5. Conclusions

In the current conditions of diffusion of soil degradation and desertification processes, as well as soil consumption due to the expansion of artificial covers, and in absence of realistic possibilities to reverse this trend in the short term, it is of primary importance to maximize the efficiency of agricultural practices, contextually limiting the exploitation and degradative phenomena of a non-renewable resource, considering the concept of "soil quality" as "soil functionality", in terms of aptitude to express their chemical, physical and biological potentialities, based onto their different pedogenetic structure [5.3 – 5.7].

Being the results of cultural techniques strictly connected to the soil quality, managing a substrate optimized for the machinery and crops is the first parameter to maximize the cultural results, in the economic concept of marginal productivity pursuits in the use of production factors, respecting the environmental sustainability of income-intensive crops.

In this perspective, the destoning system presented was very effective in the long-term reclamation of soil stoniness, having easily obtained from a "B" workability class and 4.15 DD soil, an arable layer of 600 mm depth of "A" workability class and 0.1 DD. This result was achieved without changing the level of the field plan and the structural characteristics of the fine earth, in a perspective of long-term soil stability, which are the main disadvantages of other destoning systems commonly adopted in agricultural land, in addition to the low processing depth (not over than 300–400 mm), and destoned arable layer obtainable, of the destoning machines currently available.

The validation of the described agro-mechanical advantages in the evolution of the structural characteristics of the destoned soil and yields of the cultivated crops will lead to evaluating the perspective of engineering a machine able to carry out automatically and continuously the described deep burial destoning system. Even though a little percentage of small classes coarse fragments can be useful in the preservation of soil structure, this kind of machine could also be designed to screen and stratify even the Z class fractions, in the same or different draining layers, proportionally increasing the fine earth topsoil and soil texture quality, depending on the tolerances of the cultivation machines and needs of crops.

The achievement of this objective will make this system cost-effective and contribute to enhancing in long-term the quality of stony soils, recovering non-renewable resources, and promoting the implementation of precision farming techniques, such as minimal tillage, variable rate precision sowing, localized fertilization, and weeding, to improving crop yields, machinery efficiency - reducing at the same time their wear - and profitability of the agricultural job in a wider number of potential users.

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All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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6. Assessment of Stony Soils Workability by Noise and Acceleration Measurement

With the evolution of precision farming technologies (geo-positioning, auto-guidance and ISOBUS), the workability disturbance degree induced by the coarser fractions of the arable layer penalizes the operational capabilities of the machines and the cultivation results. In particular, for precision seeders operating in stony soils, up to two thirds of the operational potential reduction was detected, with evident inefficiencies also in the seeding quality.

For the further evaluation of the agro-economic advantages of soil remediation, the levels of vibrations and noise produced during sowing were, therefore, deemed as dependent on the workability disturbance degree generated by the skeleton; to verify whether these noise and vibration values can be used to monitor seeding performance and provide information on the correct seeding speed to the operator via display or directly to the tractor's ECU, as explained in the following chapter.

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Article

Workability Assessment of Different Stony Soils by Soil-Planter Interface Noise and Acceleration Measurement

Pietro Toscano, Maurizio Cutini, Alex Filisetti, Elia Premoli, Maurizio Porcu, Nicola Catalano, Carlo Bisaglia and Massimo Brambilla

Abstract: Sowing is critical for successful crop establishment and productivity, particularly in precision agriculture management strategies. However, topsoil characteristics directly affect agribusiness maximization (i.e., crop-yield increase, machinery efficiency, operating-cost reduction) even in the most advanced farming management techniques. The excessive presence of coarse fractions or stones in arable soil layers prevents modern machinery from reaching optimal efficiency. This work focuses on sowing to verify whether the vibration and noise arising during this operation significantly change with varying soil conditions according to the stoniness degree of disturbance on soil workability. To make this assessment, an experimental sowing activity was carried out on four soil plots with two different disturbance degrees. The results confirmed that the noise and acceleration of the sowing machine significantly correlated with the soil disturbance degree and related workability profile.

Keywords: sustainable agriculture; precision farming; stoniness degree of disturbance; stony-soils workability; seeder machine; seeding speed

6.1. Introduction

In modern agricultural management strategies, especially in precision-agriculture (PA) systems, sowing is one of the key factors influencing crop establishment and yield. Usually, before sowing, various tillage methods and types of machinery are used to prepare the soil, according to soil characteristics, farming techniques and crop needs, to destroy weeds and pests and improve the structural conditions of the arable layer, so as to maximize the efficiency of seed planters, and enhance seed germination and the growth of seedling roots. In the most advanced farming management typologies, maximizing arable farming outputs - in terms of crop yield, machinery efficiencies and reduction in operating costs - directly depends on topsoil quality. When defining and assessing the textural characteristics of arable layers, soil fractions over 2 mm in diameter (gravel and stones) are usually excluded because they are considered inert fractions.

However, an excessive presence of coarse fractions or stones in the soil's arable layers hinders or is incompatible with the operational requirements of modern cultivation techniques and machinery (i.e., minimal tillage, precision sowing), which require fields without obstructions and topsoil of fine earth to work at their best [6.1–6.3].

This work focuses on sowing to verify if the vibration and noise arising during such operation significantly change at varying soil conditions according to the stoniness disturbance degree on soil workability. The importance of vibration on the seed metering performance has been also highlighted for the design of a seed metering device and entire seeder, as well as the determination of operation speed [6.4, 6.5].

6.1.1. Sowing Efficiency Issues: Precision Seeders

In the panorama of digital and precision farming machinery, seeders are a key tool for optimizing crop results. According to different sowing requirements, various types of precision seeders have been developed to meet the needs resulting from the geographical environment, farm scale, mechanization level and crop type of different countries, for both tilled and untilled soils [6.6, 6.7].

Across their different types and structural and operational characteristics, such machines maximize sowing efficiency in terms of costs and time savings. Moreover, precise seed positioning along the row and at the proper sowing depth avoids seed wastage and fosters optimal crop growth.

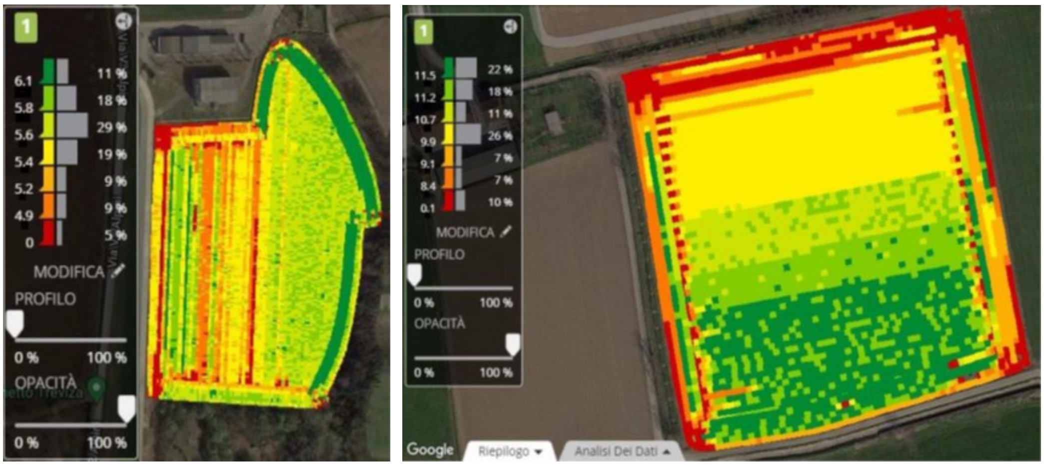
Precision seeders are generally semi-portable machines consisting of a variable number of independent planter units fixed to the frame. Each element, therefore, constitutes a complete sowing unit, consisting of a hopper, distribution and damping devices, seed covers and a compaction device. In some cases, they can be combined with equipment for complete and minimal tillage or equipped with simple implements suitable for opening the furrow for depositing the seed in the firm soil (sod seeding).

Under optimal soil conditions, mechanical seeders operate at speeds between 5 and 7 km h^{-1} with power requirements varying between 1.5 and 2.0 kW per row. Pneumatic seeders can operate at speeds of up to 10–12 km h^{-1}, ensuring good uniformity of distribution, albeit with higher power requirements, typically 4–5 kW per row [6.8]. The planters are suitable for precision planting under a working speed of 6.9 km h^{-1} [6.9]. The most recent ISOBUS [6.10] models, with electrically driven seeding units, tractor auto-guidance system and global navigation satellite system (GNSS) positioning, can operate at speeds of up to 15 km h^{-1} with high levels of precision [6.11]. Various authors have evaluated the operational performance of different seeders in different areas and for different crops.

However, neither bibliographic references nor technical documentation report correlations between machinery performances and soil condition, assuming that the soil is optimal for the performances of the described machines [6.12-6.15]. On the contrary, the type and structural conditions of the soil on which sowing occurs heavily affect the operational efficiency of seeders in terms of waving, humidity, and seedbed preparation methods: the presence of skeleton in the arable soil layer is widespread in a great part of the world’s arable lands [6.16, 6.17].

One of the main factors characterizing the efficiency of a seeder in terms of work rate, with the related costs for the tractor, operator, and fuel consumption, is the maximum allowable forward speed. Apart from technical considerations, such speed can depend on soil composition. For example, Figure 6.1a reports operation on soil with high skeleton which allowed a maximum speed of 5.6 km h^{-1}. Figure 6.1b reports the performance of the same tractor and seeder during an experimental sowing experience at various forward speeds on soil without skeleton, correctly sowing at 11.5 km h^{-1}. In this last case, the limit was the maximum power of the tractor used.

Research on sowing quality associated with high speeds [6.18, 6.19] report operational limits due to excessive lateral soil throw, reduction in furrow backfill and interactions between adjacent furrows. In addition, they showed potential for new opener technology to increase operating speeds, increasing the timeliness of sowing, grain-yield potential and lowering total seeding time per season [6.20, 6.21], encouraging the approach to technical improvements in the implement specific to particular soil conditions.



(**a**) (**b**)

Figure 6.1. The forward speed of two different sowing operations on soil with different skeleton levels: (**a**) reports operation on soil with high skeleton which allowed a maximum speed of 5.6 km h^{-1}; (**b**) reports the same tractor and seeder on soil without skeleton correctly sowing at 11.5 km h^{-1}.

6.1.2. The Stony-Soils Disturbance Degree

The type and amount of coarse fractions define the workability class of soils as a function of the degree of disturbance (DD) caused to cultivation machinery (Figure 6.2) [6.22]. Soil stoniness can severely impair the efficiency of this machinery, in particular of seeders, in terms of both sowing effectiveness and structural integrity, even for those equipped with the most advanced vibration-damping systems and downforce control of sowing elements [6.23].

Understanding the effect of soil conditions on sowing performance in terms of precision and work rate requires the possibility of monitoring the parameters correlated with the operation.

The monitoring of some parameters is already adopted in rotating machines for the diagnostic analysis of the correct functioning. For example, vibrations and noise could be specific signals that indicate abnormal functioning [6.24]. Focused engineered sensors measuring vibrations have been developed for measurements on a hay-handling machine and have confirmed the capability of the online monitoring system to diagnose malfunctions. The proposed measuring system could also be used to improve the durability of agricultural machinery [6.25].

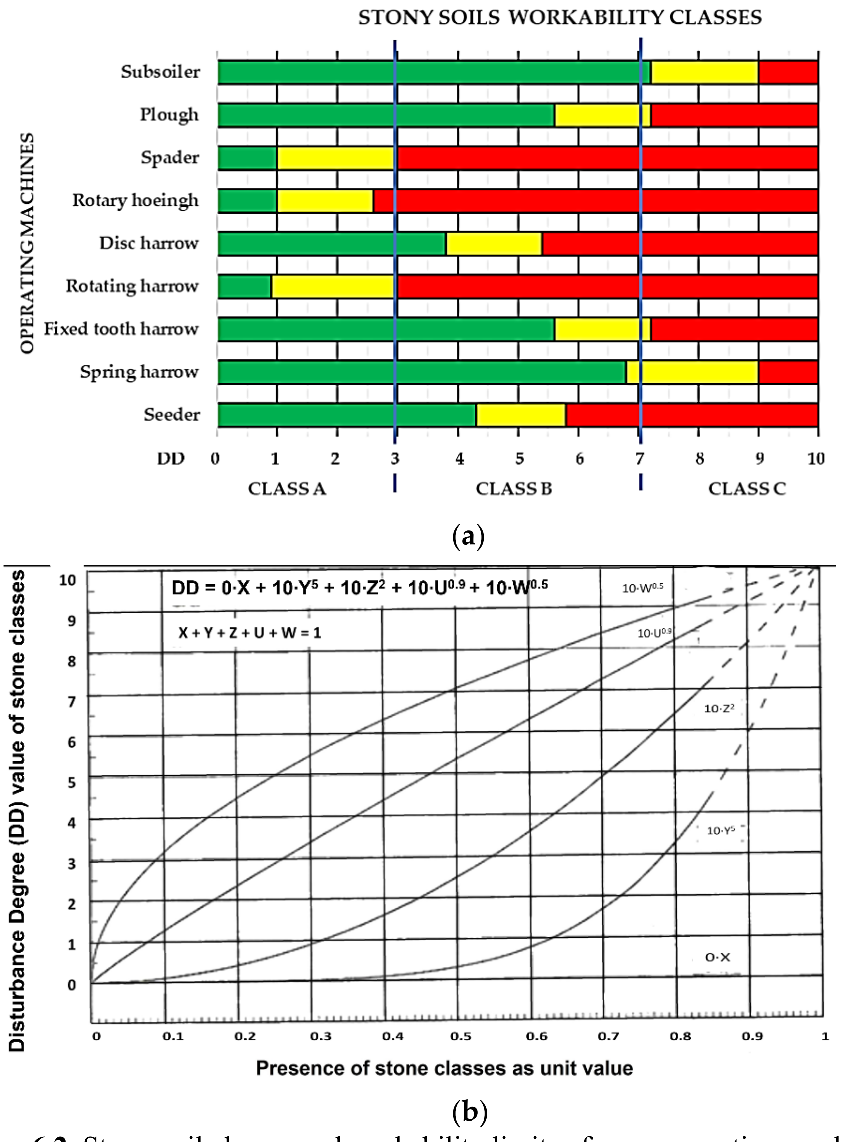


Figure 6.2. Stony-soil classes and workability limits of some operating machines (**a**), according to the stone classes disturbance degree (**b**) [6.22].

A purpose-designed array of instruments has been developed to install accelerometers and microphones for evaluating grain losses in key points of combined harvesters [6.26].

With this aim, this study focuses on the possibility of evaluating whether the level of vibration/acceleration or the noise of seeder units upon their impact with soil could be a signal correlated to the seeding quality or mechanical protection of the machine when operating on stony soils. Reducing vibration at a seeder distributor element to optimize sowing quality (uniform distribution) has also been developed as a patent [6.27].

This work aims to verify whether vibrations and noise during sowing can be measured and acquired and can identify significant changes in soil conditions according to the stoniness degree of disturbance on soil workability.

The results could also be discussed alongside the recent development of the ISOBUS function tractor implement management system (TIM). TIM is an ISOBUS-based agricultural technology system which enables the implement to control tractor functions such as, for example, forward working speed.

6.2. Materials and Methods

6.2.1. Soil Geoelectric Analysis/Test Plots

At the Council for Agricultural Research and Economics (CREA) experimental farm in Treviglio, Bergamo, Italy (45°31’14” N; 9°35’27” E; +128 m asl), in a soil classified as Calcic Skeletic Mollic Umbrisol, with neutral-sub alkaline pH, according to the International Union of Soil Science (IUSS) classification [6.28], a geoelectric analysis followed by the application of a classification algorithm on the 0–1 m deep soil’s resistivity values resulted in the zoning of three homogeneous macro areas (Figure 6.3) [6.29].

Figure 6.3. The shape of the homogeneous geoelectric soil zones.

Profile No. 4 is representative of soil class “A”, consisting of soils with a depth of about 600 mm, with a medium sandy texture, characterized by a surface layer of about 200 mm of dark-brown color, with skeleton (25–35%) consisting of pebbles and gravels, of moderate subangular polyhedric, fine and medium structure and with fine pores. On the surface, there is a relatively abundant presence of pebbles. From a depth between 200 to about 600 mm, there is a brown-color layer, with abundant medium and large skeleton (50–60%) with weak fine subangular polyhedric structure and fine and medium pores. At depths over 600 mm, the skeleton is very abundant (>70%), consisting of pebbles and gravel.

Profile No. 1 represents soil class “C”, with soils with a depth of about 1000 mm, medium to silty texture, characterized by a surface layer of about 200 mm of dark-brown color, with 10–15% skeleton consisting of small and medium gravel; fine and medium polyhedric structure; and abundant fine pores. From 200 to about 700÷800 mm deep, there is a brown/olive-brown layer with a frequent (25–35%) medium and large skeleton. It has medium and large angular polyhedric structures and fine pores. Over 700÷800 mm deep the skeleton is abundant (35–50%), consisting of pebbles and gravel.

Two test plots of 10 x 20 m surface area were chosen (P1 and P3) as the plots to carry out deep burial stone reclamation digging the soil up to 1 m deep (Figure 6.4a). The dug soil was then sieved (Figure 6.4b), gradually discharging in the trenches the stones retained by the grid (Figure 4c); then, the filling of the trenches with the sieved fine earth, including skeletal fractions up to 40 mm (classes Y and Z) was completed (Figure 6.4d); levelling and compacting the layer of fine earth was performed with repeated passages of the crawler excavator (Figure 6.4e).

Two other contiguous plots of the same area of undisturbed soil were delimited as control tests (P2 and P4) (Figure 6.5) [6.30].

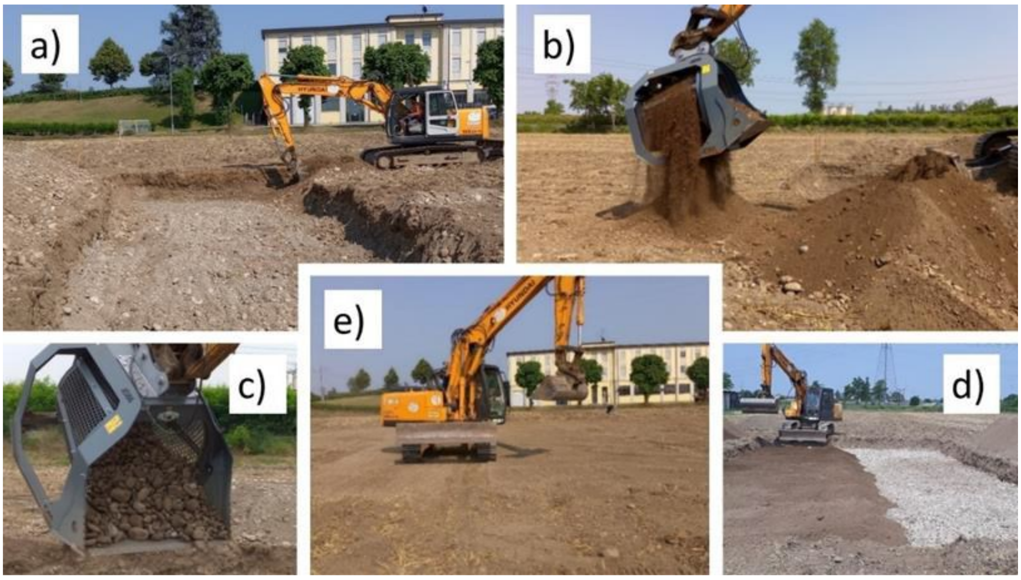


Figure 6.4. Diagram of the processing phase: (**a**) trenches digging; (**b**) soil sieving; (**c**) discharging of retained stones in the trenches; (**d**) refilling of trenches with sieved fine earth; (**e**) compaction of sieved fine earth layer.

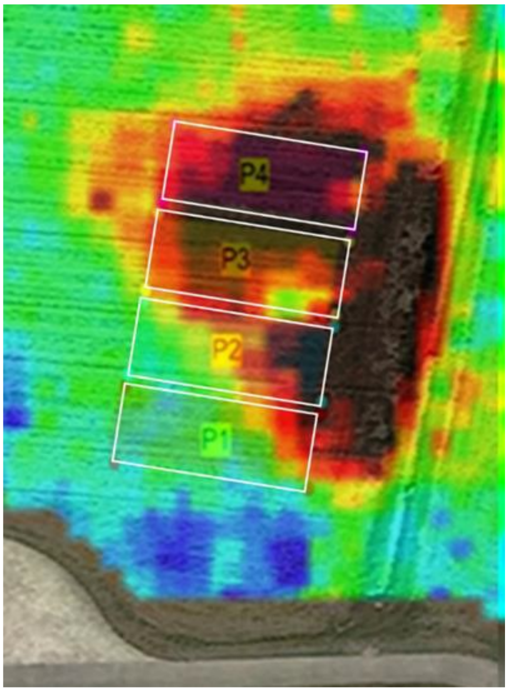


Figure 6.5. Experimental plots on soil geoelectric profiles (0–1 m deep): P1, P3 reclaimed plots; P2, P4, undisturbed control plots.

As a result, a clear improvement in the topsoil appearance was obtained without changing the plane of the field (Figure 6.6).

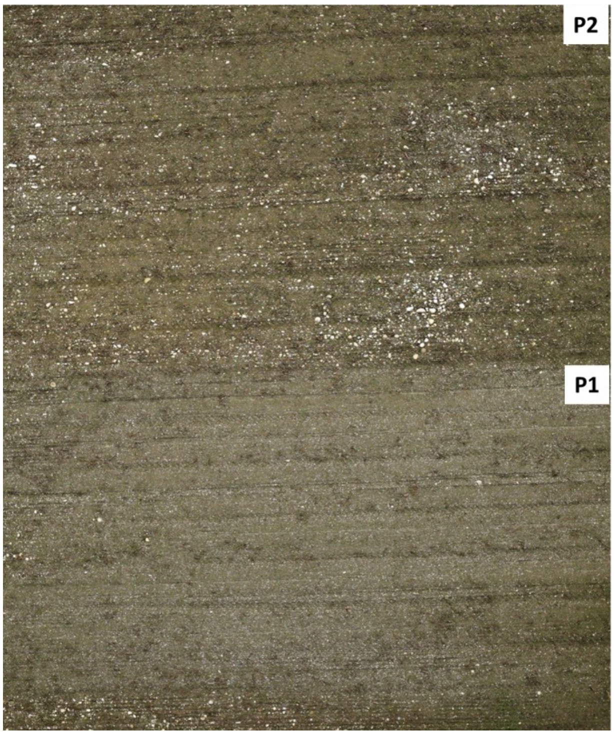


Figure 6.6. Appearance of the topsoil on the P1 (reclaimed) vs P2 (undisturbed) experimental plots (40 m aerial picture).

6.2.2. Georadar Survey

The results of the described stone reclamation system on soil profile were evaluated by performing the Ground Penetrating Radar (GPR) mapping of the experimental plots using a GSSI UtilityScan RLT3 with 350 MHz HyperStacking antenna (Geophysical Survey Systems Inc., Nashua, NH, USA; Figure 6.7) [6.31].

(**a**)

(**b**)

Figure 6.7. (**a**) GPR device used for the survey; (**b**) GSSI UtilityScan during the survey on experimental plots.

6.2.2.1. The Ground-Penetrating Radar Technology

GPR is a non-invasive geophysical technique [6.32] which employs radio waves, typically in the 10 to 3000 MHz frequency range, to map features buried in the ground. This nondestructive method detects the reflected signals from subsurface structures. When the signal hits a target or a boundary between materials having different permittivity values, it may be reflected from the surface and then detected by the GPR device. GPR is a convenient methodology for the imaging of subsurface features. It is an efficient investigation tool for studying the variations in the soil [6.33–6.35]. This technology can be used in agriculture to estimate the spatial pattern of lithological subsurface layers and reveal layer discontinuities [6.36]. This technique provides significant advantages over traditional methods such as soil cores or excavation.

6.2.2.2. Ground Penetrating Radar Survey

The GPR survey has proven able to detect the difference between two different contents of the soil. The survey was carried out in the 4 areas mentioned hereafter: A (P1, P3: reclaimed) and B (P2 and P4: undisturbed). The difference between A and B is related to the first shallow layer (600 mm depth). Soil A is more homogeneous than soil B because the stones have been removed and buried under the arable layer.

Twenty-two GPR profiles were collected inside the A and B areas by recording GPR traces (inline sampling) every 1 cm, with the maximum depth of investigation being 1.65 m (83 ns in terms of time window).

It has always been possible to detect the difference between soil A and soil B in the acquired profiles. The low backscatter of the signal is due to the lack of agglomerations and stones in the reclaimed areas (A) (Figure 6.8); meanwhile, in non-reclaimed areas (B), the signal has greater backscatter and attenuation along the depth axis (Figure 6.9).

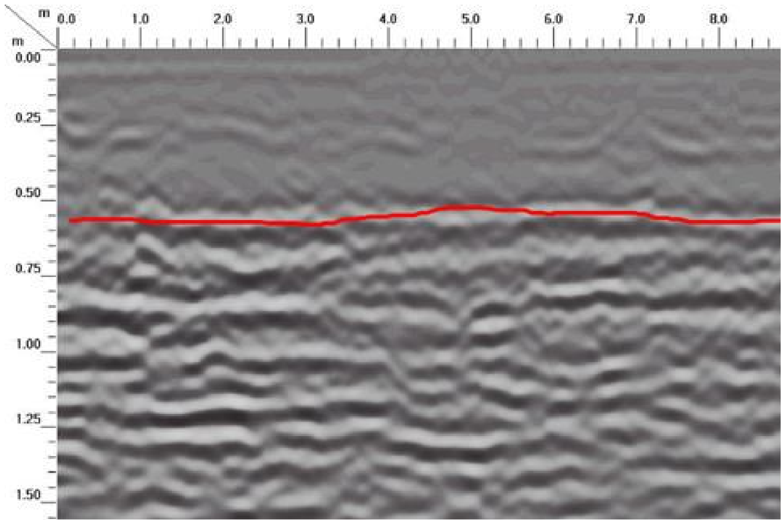


Figure 6.8. GPR profile collected on soil A (reclaimed soil). The red line shows the bottom layer of reclaimed soil.

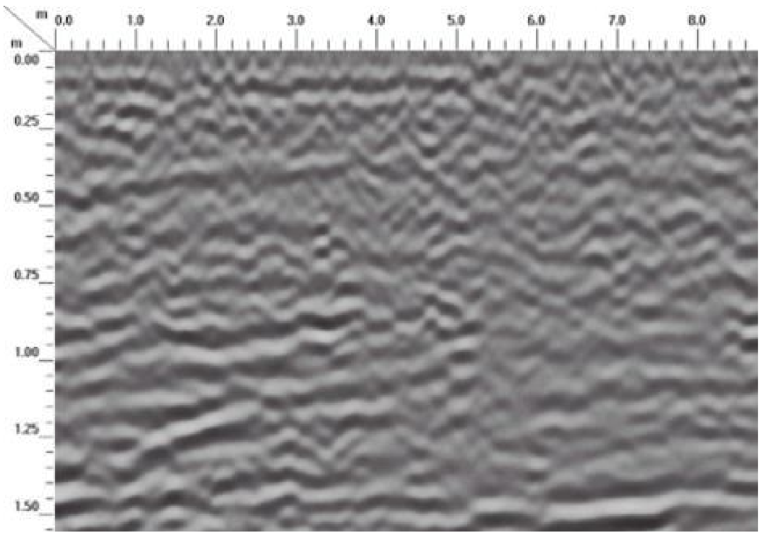


Figure 6.9. GPR profile collected on soil B (undisturbed) soil. The shallow layer is more scattered compared to the Figure 8 profile.

6.2.3. The Machines Used

On all plots, a preliminary seedbed preparation was carried out by harrowing with a combined tiller (Figure 6.10) at an approx. depth of 200 mm for the rupture of the soil crust and the burial of the previous crop residues.

The machines used were chosen to ensure the data record matched the chosen plots. For this reason, geo-positioning and auto-guidance systems were necessary to precisely ensure the three longitudinal passages.

The chosen tractor was a 117-kW nominal power tractor with continuously variable transmission (CVT) equipped provided with commercial PA technologies, consisting of a navigation system: GNSS receiver; real time kinematic (RTK) antenna, a terminal unit (VT), and a drive-wheel electric system for auto-guidance. The seeder was a 4.0 ISOBUS, pneumatic, 3 m wide, with 24 planter units, combined with disks (Figure 6.11).

Figure 6.10. Seedbed preparation harrowing

Figure 6.11. The sowing tests setting.

6.2.4. Survey Methods

The considered factors are:

- Plot: 4, 2 reclaimed (B1; B2) and 2 undisturbed (NB1; NB2);
- Accelerometer position: 1 to 5;
- Axis of solicitation of the accelerometers: x; y; z.

The method involved three passes per plot at 1.25 ms^{-1} (4.5 km h^{-1}). The forward speed was established based on the experience of the operator as the maximum allowable in the worst-case plot scenario and was kept constant in all the plots.

The acquired signals resulted in the three axes of the accelerometer (x = longitudinal; y = lateral; z = vertical) for all the 5 sensors and the microphone's sound pressure level.

With this setting, the analyzed factors resulted in 16 channels. The frequency of acquisition was 1 kHz for the accelerometers and 50 kHz for the microphone.

Regarding noise, it will be reported as sound pressure level (SPL) and expressed in decibel (dB) unit. In order to consider the sound perceived by the human ear, the Aweighted decibel (dBA) was adopted. Since it is assumed that the sound pressure levels may be higher than 85 dBA, indicating a noisy environment, it is believed that the C-weighted decibel (dBC) may be more suitable for the purpose of the study. For this reason, in addition to the commonly adopted dBA, approach, the measurements will also be analyzed in dBC.

Regarding acceleration, the analysis included root mean square (RMS), maximum and minimum acceleration.

Consequently, the measurements made were:

- Accelerations: 3 (rep) x 5 (positions) x 4 (plots) x 3 (axis) x 3 (RMS, max, min) = 540;
- Noise: 3 (rep) x 4 (plots) x 2 (weighted dB) = 24;

for a total of 564 values.

6.2.5. Instruments

The study focused on the measurement of acceleration and sound pressure. The sensors used were accelerometers and microphones. The sensors, software and acquisition system are shown in Table 6.1.

Table 6.1. The instruments used.

Instrument/Material	Make/Model
Triaxial accelerometer	PCB 356A02
Triaxial accelerometer	Dytran 3263A2
Microphone	PCB 378B02
Data logger	Dewesoft Sirius
Data-acquisition software	Dewesoft X3
PC laptop	Panasonic CF31

The accelerometers used were all triaxial: three were positioned on the distribution elements of the machine, i.e., one on the left (position 1), one in the middle (position 2) and one on the right (position 3). Another was positioned on the main frame of the seeder (position 4), and the last one was placed on the pivoting roller (position 5).

The microphone was positioned in the horizontal position on the ladder railing and pointed toward the back of the machine (Figure 6.12 a, b).

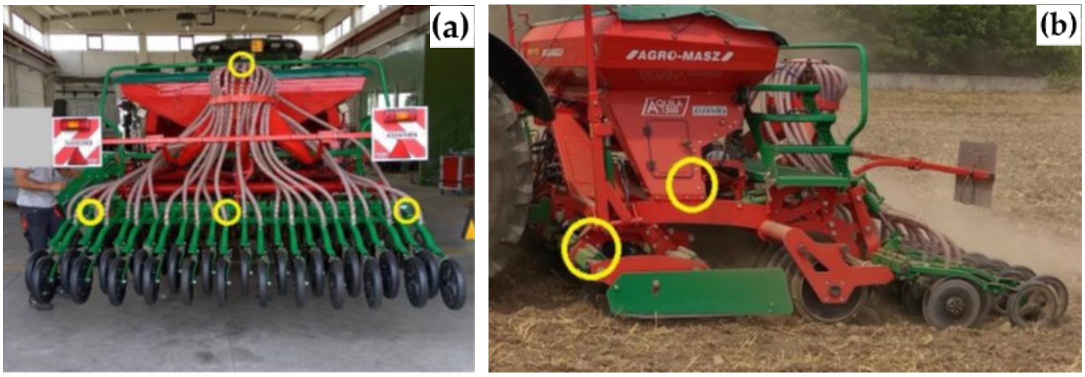


Figure 6.12. (**a**): the position of the triaxial accelerometers 1, 2 and 3 (on sowing elements, yellow circles) and the position of the microphone in the middle of the ladder railing of the upper portion on the hopper (yellow circle). (**b**): the position of the triaxial accelerometers 4 and 5 (yellow circles).

6.3. Data Analysis

The data acquired were processed with Minitab 17 statistical software [6.37] using the analysis of variance (ANOVA), which applied a generalized linear model (GLM) [6.38]. The plot (NB/B), the sensor position on the frame (1 to 5), and the acquisition axes (x, y, and z) were assumed to be fixed factors, while the root mean square (RMS) of the accelerations and the maximum and the minimum values of the time histories were the dependent variables.

The Levene test ($p < 0.05$) [6.39] evaluated the homogeneity of the dataset's variances before the variance analysis.

6.4. Results

The results as root mean square (RMS) are reported in Table 6.2.

The highest accelerations were found at the roller and ranged from 0.3 g in the destoned soil to 0.59 g in the undisturbed plots with a high skeleton level. The lowest accelerations, as expected, were at the frame, where the differences were less clear.

The mean acceleration value at the elements on the stony soils resulted in about double the destoned one.

Interestingly, the highest values were not found exclusively at the vertical axis, but all three axes were essential for the study. This aspect was observed, above all, at the pivoting roller (position 5), which appeared to be the most interesting: the longitudinal stress has the highest value (position 5; x axis).

Table 6.2. RMS value of the acquired acceleration.

Plot	Accelerometer Position	Axis (g)		
		x	y	z
B1	1	0.12	0.09	0.20
	2	0.09	0.13	0.17
	3	0.11	0.13	0.23
	4	0.06	0.08	0.15
	5	0.29	0.18	0.26
NB1	1	0.27	0.21	0.39
	2	0.18	0.25	0.34
	3	0.20	0.23	0.38
	4	0.10	0.13	0.22
	5	0.59	0.35	0.48
B2	1	0.14	0.14	0.24
	2	0.10	0.14	0.19
	3	0.10	0.11	0.22
	4	0.06	0.08	0.14
	5	0.30	0.20	0.26
NB2	1	0.23	0.21	0.37
	2	0.17	0.23	0.32
	3	0.19	0.24	0.38
	4	0.10	0.13	0.20
	5	0.47	0.31	0.41

The application of the analysis of variance (ANOVA) not only on the RMS values but also on the maximum and minimum values of the acquired time histories indicated the possibility of using acceleration to define the sowing parameters (Table 6.3).

The plot, the sensor position, and the kind of sensor were all found to be significant factors ($p < 0.05$). Moreover, the data should be considered attentively as it is very interesting to note that their interaction was also significant. All the five accelerometers recorded significant differences. The accelerometer at the frame was the one with the smallest difference while that at the roller recorded the most differences. Regarding the accelerations of the distributors, measured as RMS, although these were the lightest elements, they were not those with the highest RMS acceleration, probably because they were fixed to the frame.

Table 6.3. Results of the ANOVA.

Source	RMS 960904 p-Value	Max 960904 p-Value	Min 960904 p-Value
Plot	0.000 ***	0.000 ***	0.000 ***
Position	0.000 ***	0.000 ***	0.000 ***
Axis	0.000 ***	0.000 ***	0.035 *
Parcel x position	0.000 ***	0.000 ***	0.000 ***
Plot x axis	0.000 ***	0.005 **	0.529 ns
Position x axis	0.000 ***	0.000 ***	0.000 ***
Plot x position x axis	0.012 *	0.017 *	0.058 ns

**** = p < 0.001; ** = p < 0.01; * = p < 0.05; ns (not significant) = p > 0.05.*

As expected, the ANOVA analysis of the peak accelerations, both maximum and minimum, also gave significant results, confirming the different behaviors of the seeder when changing the plots. However, it must be noted that, in this case, it could be challenging to use this signal for monitoring in continuous mode and active optimization.

The results of the phonometric survey are reported in Table 6.4.

Table 6.4. Mean values of sound pressure level and result of the Tukey test

Plot	Mean	Grouping	Plot	Mean	Grouping
	dBA			dBC	
B1	90.0	c	B1	102.1	b
NB1	98.7	a	NB1	110.5	a
B2	92.3	b	B2	104.1	b
NB2	98.2	a	NB2	110.2	a

Items with different letters are significant for p < 0.05.

In this case, too, a significant confirmed difference in noise value was found between the different plots. Both dBA and dBC gave significant results with very high differences (6 dBA and dBC). Therefore, both values could be adopted for monitoring the seeding.

In this case, there is no signal problem as the software was already set up to provide the drive signal as both dBA and dBC. However, the results are of interest because it must be considered that noise is also the main feedback for the operator to decide the correct forward speed or the quality of the seeding.

6.5. Discussion

The question of the quality and speed of sowing is widely debated and current. The same sowing speed affects the outcome of the sowing. An increase in speed leads to a high degree of soil disturbance, inaccurate laying of the seed and suboptimal closure of the furrow. The issue was addressed by considering mainly two aspects: the properties of the soil and the technical and mechanical structure of the seeder.

In the literature, the issue is of particular interest in the fields of minimum tillage and soils with a high degree of stony disturbance. Many agricultural soils have variable percentages of coarse fractions in their arable layer, which interfere with crop growth and machine working. In addition, different techniques are available for destoning such as (*i*) collection and removal, (*ii*) on-site stone crushing, and (*iii*) stone burial. All these methods are expensive.

In addition, the further advent of geo-positioning, self-driving and ISOBUS technologies have highlighted how the workability of the soil is a bottleneck for such machines. The limit highlighted by the operators is in the mechanical stress on the implement, which limits the operating speed to one third of the maximum possible.

With this aim, this study was performed to investigate whether it was possible to use noise and/or vibration values to monitor sowing performance in stony soils.

Four soil plots of two different disturbance degrees were prepared and an experimental sowing was carried out. The chosen forward speed of this experiment was 4.5 km h^{-1}, chosen as the maximum allowable speed on a stony plot by the operator.

Sowing trials on reclaimed and undisturbed plots showed that the noise and acceleration measured and acquired significantly differed when changing the soil conditions according to the stoniness degree of disturbance (DD) on soil workability.

Results confirmed that both noise and acceleration were significantly correlated with soil DD, to the point of being able to hypothesize their use as indicators to optimize mechanical operation.

Moreover, modern tractors with a global navigation satellite system (GNSS), auto guidance and ISOBUS seeder could also work at 15 km h^{-1}. This highlights not only the three-fold higher field efficiency of the machines but also the correct way of using the engine of high-powered tractors, whose power is limited by the maximum allowable speed. Therefore, the economic considerations about destoning could enable a new approach considering not only the current growing scarcity of further farming land, but also the opportunities offered by new digital technologies. For example, it is possible to imagine providing information on the correct forward sowing speed to the operator by means of acoustic or visual signals on the display or directly to the tractor's electronic control unit. The experiment also pointed out the capability of purpose-designed sensors (i.e., accelerometers) and their most interesting measurement axis. Moreover, use of the Tractor Implement Management technologies (TIM) system could optimize the operational efficiency of precision seeders in terms of working rate. TIM enables automatic operation, similarly to an on-the-go sensor, at the most suitable forward speed compatible with the structural characteristics of the machine depending on the levels of acceleration or noise induced in real time by the characteristics of the soil on which the machine operates, simultaneously reducing the risks of wear or breakage, and the related costs due to downtime and repairs. TIM's main concept is to enable bidirectional communication between tractor and implement, i.e., a transfer of control in both directions, to automatically control the main operational functions of the tractor.

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7. Soil analyses and Biomass production (unpublished data).

7.1. Soil analyses

According to soil composition (Table 7.1), a substantial modification of the soil profile was obtained in reclaimed plots, starting from a class B and DD= 4.25 soil (X=0.46, Y=0.20, Z=0.14, U=0.15, W=0.05), to an arable layer of fine earth of about 600 mm deep, corresponding to a class A and DD = 0.2 soil (X=0.66, Y=0.20, Z=0.14, U=0, W=0), with U and W stone classes constituting a draining layer of about 400 mm. This value falls in green zone (without limitations) for all operating machines commonly used in herbaceous crops cultivation, as shown in Figure 5.4.

Table 7.1. Soil composition in reclaimed plots (10/10/2022)

	Total	Fine earth	Skeleton ≤ 40 mm
Kg	53.4	35.3	18.1
%	100.0	66.1	33.9

The fine earth composition and O.M. content in experimental plots (Table 7.2), result similar in the undisturbed soil (P2, P4) vs. the P1 plot, except for the Clay, while P3 shows higher Sand and lower Silt and O.M. content, with Clay similar to P1, and higher than Undisturbed plots (P2, P4).

Table 7.2. Fine earth composition of topsoil (0-200 mm) in experimental plots (24/10/2022)

	P1	P2	P3	P4
O.M.	2.12	2.77	1.82	2.95
Sand %	69.8	72.7	77.6	74.2
Silt %	22.7	22.4	15.0	20.9
Clay %	7.5	4.9	7.4	4.9

7.2. Biomass production

In addition to the reduction of the DD of the soil, the studied reclamation method has also been validated by the biomass production of cultivated crops (Table 7.3).

In the 2021 winter crop (Triticale) sown at 180 kg/ha density and 125 mm row spacing (Figure 7.1), there was a 20.6% increase in the average biomass yield in reclaimed plots compared to undisturbed plots.

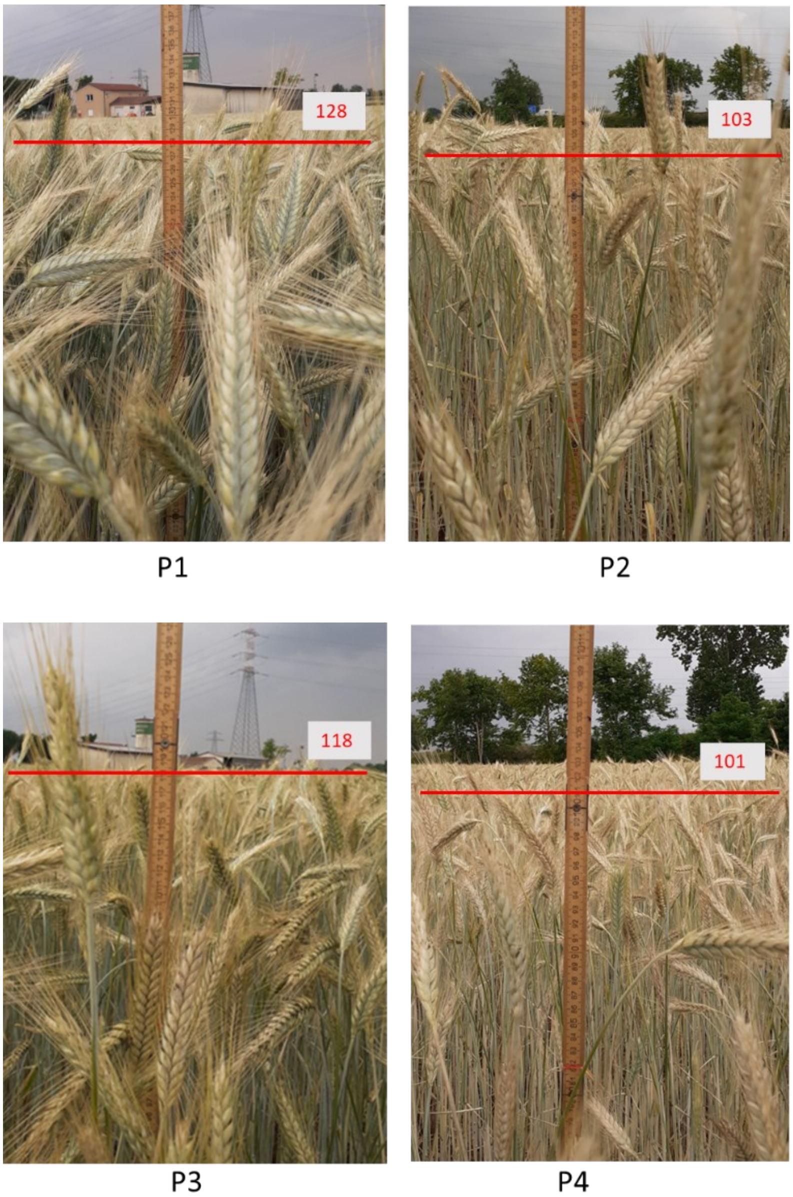

Figure 7.1. Height of Triticale at harvest time (31/05/2022) in the experimental plots (P1, P3: reclaimed; P2, P4: undisturbed)

Also for the subsequent summer crop 2022 (Sorghum), sown at a density of 30 kg/ha and row spacing of 375 mm, despite the extreme summer drought that strongly penalized plant growth, there were increases in biomass at harvest of 23.1% in the average yield of reclaimed vs. control plots.

Finally, for the last monitored winter crop 2022 (Barley), sowed at 80 kg/ha density and 125 mm row spacing, despite the continuing winter/spring drought conditions, the reclaimed plots have showed higher yields (Figure 7.2), with average biomass increase of 28,7% in reclaimed vs. control plots.

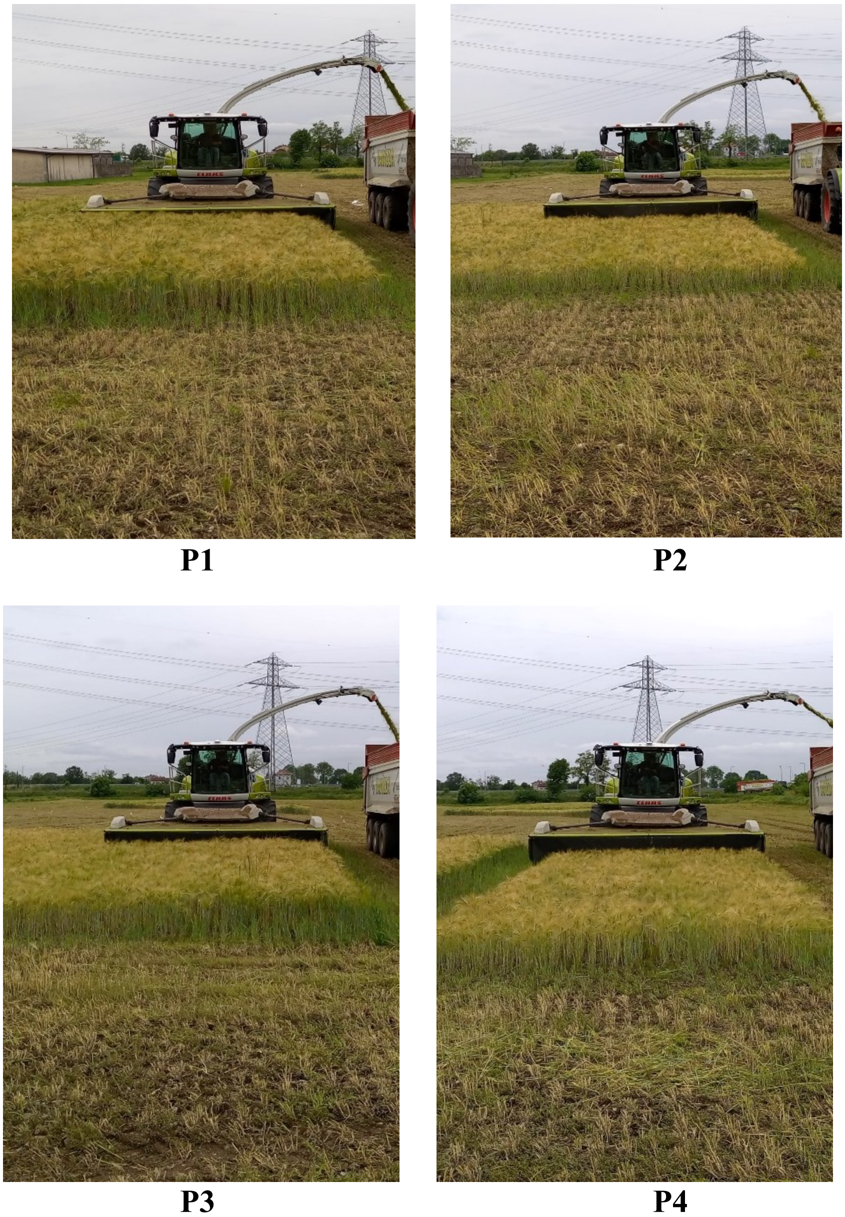

Figure 7.2. Biomass of Barley at harvest time (17/05/2023) in the experimental plots (P1, P3: reclaimed; P2, P4: undisturbed)

Moreover, regardless of the crop, it can be noting a continuous increase in difference (Δ%) of average crop yield (Av) between thesis, that indicate a good evolution in restoration of structural conditions and fertility of soil after the reclamation.

Table 7.3. Crop's Biomasses at harvest time (t/ha)

P	Triticale (31/05/2022)	Sorghum (05/10/2022)	Barley (17/05/2023)
1	22.5	16.6	24.6
2	18.1	13.3	18.2
3	20.7	15.4	22.4
4	17.7	12.7	18.2
Avg(1,3)	21.6	16.0	23.5
Avg(2,4)	17.9	13.0	18.2
Δ%	20.6	23.1	28.7

8. Conclusions

The state of the art on the destoning methods in agricultural soils shows the availability of various techniques and machines designed for and usable in different environmental conditions and for different cultivation needs.

Given the operational needs of agro-industrial crops and the diffusion of precision farming techniques, it is of particular importance to operate on arable layers composed of fine earth only, or with a workability disturbance degree compatible with cultivation machines (e.g., precision seeders).

This is the discriminating factor in the management of coarse fractions, also considering the possible negative effects of the common methods of stone reclamation, such as the lowering of the field plane, in the case of stone removal, or the modification of the soil chemical-physical characteristics, in the case of on-site stone crushing.

On the contrary, the proposed system of coarse fractions burial below the arable layer has proven to be in a long-term more effective reclamation system, both in terms of soil workability and improvement in crop yield, as achieved in our experimental conditions, without the drawbacks of the other two systems described.

The choice of the best remediation method depends on an economic analysis in terms of amortization time of the burial operations costs, or the economic value of the stone, in case of removal, or the amendment costs to recover soil fertility after stone crushing.

The development of suitable machines for each reclamation method depends on the levels of interest and convenience in implementing more advanced cultivation methods, which require soils optimized to maximize the efficiency of the machinery and cultural responses; since, also for this field of research as well as for any other agro-industrial activity, the main parameter in the evaluation of operational efficiency and economic convenience is - or should be - the pursuit of Marginal Productivity in the use of production factors.