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REVIEW ARTICLE

A critical assessment of conservation agriculture among smallholders in the Mediterranean region: adoption pathways inspired by agroecological principles

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Abstract

Conservation agriculture (CA) is the key agricultural soil management approach for Mediterranean rainfed systems facing extreme droughts and soil degradation. Yet, CA uptake and applicability is still marginal and disputed in the Mediterranean region, where smallholder farmers are most representative. Lack of widespread adoption of CA in the Mediterranean region despite international efforts is perplexing. In order to investigate this paradox and provide solutions, we set out to examine the perceived constraints to CA implementation among farmers and stakeholders. Our approach is based on systems analysis of Mediterranean grain production systems, considering plant and livestock production, as well as sustainability and social-ecological interactions. CA promotion efforts are rarely adapted to the context of the Mediterranean region. We argue for adopting a more pragmatic and flexible approach to CA. Such an approach should be based on site-specific bio-physical and sociocultural considerations and augmented with principles of agroecology. Our review of perceived constraints allows us to suggest five pathways that could promote CA adoption in the Mediterranean across two main areas: (i) introduction of flexible, context-specific technical solutions and (ii) change of social perceptions and literacy on soil. Our five pathways aim to enhance farmers' resilience to challenges of climate and market shocks, while integrating agroecological principles that enhance ecosystem multifunctionality. We advocate using agroecological principles to enable a more pragmatic application of CA with respect to its strict application—such as continuous no-till—to rehabilitate degraded lands, to increase water use efficiency, and to improve food security and economic well-being of communities in the Mediterranean region.

Keywords Agroecology · Mental models · Strategic tillage · Soil literacy · Crop-livestock integration

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1 Introduction

Conservation agriculture (CA) has been spearheaded as a promising alternative to current unsustainable Mediterranean farming systems with their dependency on extensive soil disturbance for weed control and nutrient mineralization (Karamesouti et al. 2015; Kassam 2022). In countries such as Argentina, Australia, Brazil and Canada, CA has become the new paradigm, representing climate smart, resilient, sustainable cropping systems (Kassam et al. 2019; Fuentes-Llanillo et al. 2021; Kassam 2022). As a default farming system, CA covers up to 90% of the total cultivated land in some regions such as in Western Australia (Kassam 2022). Founded upon the three principles of no-soil disturbance, soil cover and diverse rotations, CA has been shown to improve soil quality, increase yields and reduce production costs (Kassam et al. 2012; Pittelkow et al. 2015). In dryland agricultural systems especially, application of the three principles of CA can result in greater soil quality, organic matter content, soil water capture and retention and crop productivity (Pittelkow et al. 2015; Vastola et al. 2017; Tadiello et al. 2023). There is therefore a wide consensus that greater adoption of CA in the Mediterranean region is the key for improving the resilience and productivity of farming systems (Kassam et al. 2012; Fredenburg et al. 2012; Lagacherie et al. 2018). Although a number of international and national organizations have made CA the focal point for their promotion of sustainable agricultural management systems, its uptake and applicability remains marginal and disputed in the Mediterranean region.

In this perspective, we argue for adopting a more pragmatic and flexible approach to CA. Such an approach would be based on site-specific bio-physical and sociocultural considerations, and CA would be augmented with principles of agroecology. Common CA promotion efforts in the region are often strict with tillage elimination (continuous no-till) and livestock exclusion, hence leave limited options for smallholders to deal with issues that may arise as a result. Some national (Kirkegaard et al. 2014), regional (Rodenburg et al. 2020) and international (Giller et al. 2015) perspective papers have argued for context-specific, flexible and more pragmatic application of CA before. These demands were mainly based on the bio-physical difficulties faced by CA practicing farmers that needed an alternative approach. In the Mediterranean, the unique sociocultural settings (i.e. at least 40% of the farms are smaller than 20 ha (FAOSTAT 2023) require an approach that can reach the goals of CA while being regionally acceptable and feasible.

Remarkable differences exist between the large-scale agricultural systems developed by settlers in new territories and the old highly fragmented Mediterranean agropastoral landscapes which may be responsible for lower adoption of CA in the Mediterranean. For instance, large scale, high input agricultural practices in Australia, Brazil and Canada are in striking contrast to smallholder, low input and sometimes resource-poor agriculture practiced in the Mediterranean. In that light, we discuss not only bio-physical constraints, but also the mental models of farmers regarding soil management and CA, in order to create a linked social-ecological perspective.

The agroecological approach is crucial in achieving the objectives of the European Union (EU) Green Deal, which aims to make Europe the first climate-neutral continent by 2050. Agroecology promotes sustainable and inclusive growth strategies that improve people's health, quality of life, and the environment while enhancing the incomes of farmers. According to Wezel et al. (2020), the major agroecological principles include recycling, input reduction, soil health, animal health, biodiversity and synergy. These principles are essential for transitioning to sustainable food systems that enhance food security, nutrition and environmental sustainability. Others have also contributed to the development of agroecological principles, emphasizing the importance of holistic ecological concepts and the application of these principles to agricultural systems (Gliessman 2020).

CA offers a great entry point towards agroecology in the Mediterranean region. The widely agreed necessity of reducing soil disturbance is achieved in CA, albeit with environmental and economic costs. Hence, CA is still in the level 1 (HLPE 2019) in terms of transition towards sustainable food systems, where the primary focus is reduction of environmentally damaging practices such as intensive tillage. To move CA up to level 2 (substitute conventional inputs and practices with agroecological alternatives), there is a need to offer alternative tools for soil and crop management as well as community engagement. Here, we illustrate such alternative tools and socio-ecological perspective for the smallholder farmers in the Mediterranean region. We propose that principles of agroecology are in line with and support pragmatic CA promotion, through which a new and effective approach to CA can be defined. Our approach is based on systems analysis of Mediterranean grain production systems, considering plant and livestock production, as well as sustainability and social-ecological interactions. We draw lessons from several past Mediterranean regional projects. First, we present an overview of the Mediterranean agricultural context for CA. Second, we review the perceived constraints to CA adoption in the Mediterranean region. Finally, building on extensive research experiences in Mediterranean countries, we suggest five pathways to greater CA adoption. Case study examples from a current Mediterranean CA research and development project (www.ConServeTerra.org) are used as practical examples for the five suggested pathways. These five pathways are alternative approaches embedded within agroecological principles and also with reference to research experiences across the Mediterranean.

2 CA in the Mediterranean context

Mediterranean farming and food systems can be considered a laboratory of social-ecological change, being exposed to substantial challenges that may similarly affect other world regions in future. Many of the Mediterranean countries are net food importers today, and cereals represent up to 70–80 % of the caloric intake (Benjelloun 2004; Royo et al. 2017). Recent developments such as the COVID-19 pandemic and the Ukraine war–induced disruptions in grain production and shipments highlighted the striking vulnerabilities of food systems in the Mediterranean region (and elsewhere). These vulnerabilities are exacerbated by climate change that is expected to trigger extremely fluctuating and unevenly distributed precipitation and heat waves in the Mediterranean (Schröter et al. 2005). One of the most important climate change adaptation measures is therefore to improve the capacity of soils to capture and store rainwater. Estimates of precipitation used by plants range from 10 to 25%, while the remainder is lost through runoff, evaporation and other pathways (Molden et al. 2007). These losses can be reduced through water conservation and harvesting techniques that are at the core of CA. Applying practices that increase soil organic matter and improve the capacity of soils to capture and conserve precipitation are also crucial for Mediterranean dryland agriculture to increase food security (Koohafkan and Stewart 2012).

This review focuses on Mediterranean rainfed grain production systems. Largest production area is spared for grain production in the Mediterranean reflecting the greatest wheat consumption per capita globally (Jacobsen et al. 2012; IEMED 2012). However, there is also significant area covered by the permanent crops such as olive trees and vineyards that benefit from CA practice of leaving ground cover under trees (Sastre et al. 2017; Gómez et al. 2018; Debolini et al. 2018). Several well-known scientists have estimated a potential for yield increases in drylands by 100–200% through agricultural management techniques aimed at improving soil quality. This is considerably higher than the potential for most other regions of the world (Borlaug 2002; Koohafkan and Stewart 2012). Cereal yields have globally stagnated in favourable areas since the 1990s, and there is a consensus that significant yield increases are not probable in these synthetic fertilizer saturated systems (Brisson et al. 2010; Ray et al. 2012; Iizumi et al. 2014). In contrast, Mediterranean drylands still have a noteworthy economically exploitable gap between potential yield and current farmers' yield (Koohafkan and Stewart 2012).

Despite the demonstrated advantages, and decades of ongoing promotion efforts, CA in the Mediterranean region lacks large-scale implementation. CA has been practiced in Spain since the 1980s by some pioneer farmers. Around 750,000 ha of arable crops were managed under CA in 2014 and around 1M ha (ca. 5% of arable land) in 2019 (Kassam 2022). In Italy, there is around 450,000 ha managed under CA (Kassam 2022). In Turkiye, CA was introduced in the 1990s, but it has not been widely adopted and practiced since then (Avci 2010). Recently, there has been a government push through incentives to CA machinery, but the uptake remains slow, with CA being practiced only on an estimated 100,000 ha (ca. 0.5% of arable land) of croplands (Kassam et al. 2022). In North Africa, CA has been introduced and tested over three decades (Mrabet 2011; Nefzaoui et al. 2012). By 2019, CA covered 12,500, 14,000 and 7000 ha in Morocco, Tunisia and Algeria, respectively (Kassam et al. 2022). In Morocco, CA has been promoted by the national government as one of the main pillars of the so-called Green Morocco plan, where the target is to convert around 20% of the arable fields to CA by 2030 (INRA 2023).

Until now, CA projects frequently took a direct "technology transfer" approach, requesting smallholder farmers to imitate the large-scale CA management tools (Giller et al. 2009). This "technology transfer" approach disregards the local realities such as communal stubble grazing, necessity of alternative weed management strategies in the absence of expensive herbicides, and need for legume inclusion in rotations (Ekboir 2002). For an effective promotion and widespread adoption of CA in the Mediterranean region, there is a need to analyse and map farmers' perspectives towards soil and its management, while simultaneously using educational tools (e.g. rainwater simulator) that improve farmers' appreciation and understanding of soils. CA would thus become a practice that is accessible and acceptable also to low-input smallholder farmers who currently cannot use or do not want to apply strict CA principles, as their farming systems are based on a restricted use of expensive fertilizers and pesticides and on a flexible tillage intensity as a vital strategy in controlling weeds.

2.1 CA and agroecology

While CA has relatively defined principles, agroecology holds multiple meanings, from technical innovations to wildlife-friendly farming and social and political change away from industrial-style farming (Wezel et al. 2009; Norgaard and Sikor 2019; van Hulst et al. 2020). However, one common general principle within agroecology is to work with nature in farming and to manage more multifunctional farming systems that balance ecosystem service provision (Hawes et al. 2021). Agroecology and CA are already very much aligned in terms of emphasis on soil health and diverse rotations (Tittonell et al. 2012). There are two main differences between these two systems: the socio-ecological approach of agroecology as opposed to CA's technical approach and CA's strict adherence to no-till practices as opposed to more flexible soil management of agroecology (Lacombe et al. 2018). There is a widespread consensus among the agricultural science community that one of the key management options for sustainability is to reduce soil disturbance. CA has achieved this, with some environmental costs, such as herbicide resistant weeds and reliance on glyphosate (Boutsalis et al. 2012; Beckie et al. 2019; Torbiak et al. 2021; Van Deynze et al. 2022). Agroecological farmers are still struggling to reduce tillage and minimize the reliance on excessive tillage (Peigné et al. 2007, 2016). Reducing tillage in these ecologically based systems has proven to be difficult in the absence of alternative broad-applicability weed management strategies. Hence, agroecological farmers resort to sometimes excessive tillage practices to control weeds. Implementing some of the suggested pathways may help to enable farmers to integrate both reduced soil disturbance and reliance on agrochemicals.

3 Perceived barriers to CA adoption in the Mediterranean region

Many studies have attempted to understand the main constraints to CA adoption in the Mediterranean, focusing on the bio-physical and socio-economic determinants of farmers' decision-making (Table 1) (Mrabet et al. 2022). The implementation gap of CA in a Mediterranean smallholder context has been explained by constraints such as (a) limited or no inclusion of legumes as rotational crops; (b) lack of sufficient biomass retention on the soil surface in intensive crop/livestock systems; (c) lack of access to critical inputs (e.g. specialized machinery, fertilizer and herbicides); (d) high costs of inputs; (e) lack of functional output markets for rotational crops (i.e. forages); and (f) weed pressure resulting from CA practices (Giller et al. 2015; Thierfelder et al. 2017; Devkota et al. 2022; M'hamed et al. 2022). Often absent in the list of constraints to CA adoption is the human dimension, which is rooted in socio-economic, political, cultural and mental spheres (Prager and Posthumus 2011). Another major constraint is the insufficient promotion of CA approaches that would be specifically adapted to the context of the Mediterranean region (Kirkegaard et al. 2014).

Scale of difference among the CA practicing regions in terms of farm size is significant. On average across the Mediterranean region, almost 60 and 43 % percent of farms are smaller than 50 and 20 ha, respectively (Figure 1). Larger farms are prevalent in the northern Mediterranean countries (France, Greece, Italy, Portugal, Spain and Turkiye), and smaller farms are in the southern Mediterranean (Algeria, Jordan, Lebanon and Morocco) (Figure 1). The average farm size in the Mediterranean is somewhere between the highly mechanized large lands of Americas and the low-input and small size of much of Africa. In the North and South Americas, the farms are generally large and require big machinery and high amounts of synthetic inputs for weed and soil management. In most regions of Africa, where CA has been promoted by international centres such as Consultative Group on International Agricultural Research (CGIAR), the average farm size is small, so weed and soil management can be done using human labour and animals (Jayne et al. 2003; Thierfelder et al.

Table 1 Perceived barriers influencing the adoption of CA by farmers in the literature (adapted from Mrabet et al., 2022).

Bio-physical and technical barriers
• Characteristics of farms—farm size, crops and livestock, soil fertility, slope, altitude, etc.
• Livestock integration, scarcity of pastures
• Availability, access and costs of equipment and inputs
• Site-specific conditions, field-scale effectiveness and difficulty for upscaling
• Changes in weed, disease and pest profiles, infestation and management and development of emerging diseases and pests
Political and economic barriers
• Insufficient endorsement/encouragement by governments at national and local levels of CA systems
• Scarce and limited international cooperation for CA systems uptake and upscaling
• Land tenure arrangements
• Farmer income and wealth/poverty
• Short-term economic gains and profitability, farmer's risk-taking and uncertainty
Social and cultural barriers
• Farmers' demographics, including gender, age, land ownership, family size and structure, social class, farmer's profile
• Farmers' knowledge, perceptions and attitudes, including lack of information, awareness and concern
• Social influence and conformity, neighbour's acceptance of CA, trust decisions, generational renewal at the farm

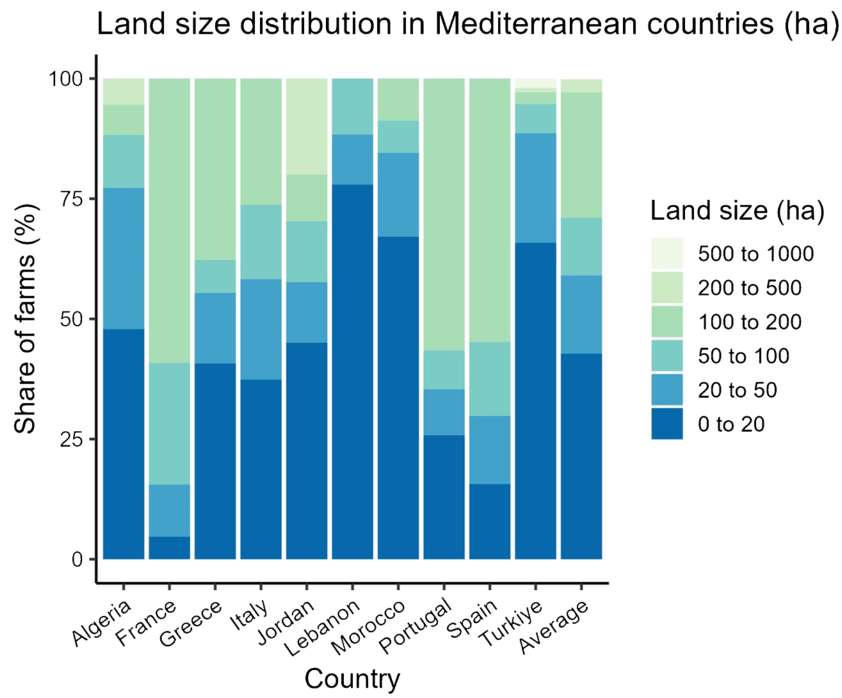

Figure 1 Land size distribution in some Mediterranean countries (FAOSTAT 2023). Only Mediterranean countries with data and significant arable land in the FAOSTAT database are presented.

2016; Lowder et al. 2016). In the Mediterranean region, however, the farm size is "average" and beyond the capacity of human labour to manage. Most farmers are at a farmland size threshold where they need machinery and expensive herbicides but cannot afford it. This is reflected in the ownership of agricultural machinery, which is particularly low in the southern Mediterranean countries compared to their northern neighbours (Figures 1 and 2). Lacking their own machinery, many farmers in the southern Mediterranean countries have to hire service providers for tillage, seeding and harvest operations. Unaffordability of direct or no-till seeding machines (CA seeders) are often cited as the one of the main constraints for greater CA adoption (Mrabet et al. 2022). For instance, Cheikh M'hamed et al. (2018) argued that the majority of farmers in Tunisia owning less than 10 ha is also a major obstacle for CA adoption because they cannot afford the specialized seeders and other inputs.

In the northern Mediterranean countries, constraints to adoption can be different from the southern Mediterranean. For instance, some Algerian studies identified the absence of affordable no-till seeders, stubble grazing and weed management as barriers (Labad and Hartani 2016; Rouabhi et al. 2018). In Morocco, the specific pedoclimatic and socio-economic conditions of farmers are the main determinants for the CA adoption (Boughlala et al. 2013; Bonzanigo et al. 2016). The education level of farmers, availability of extension services and type of landownership are the main determinants of CA adoption in Tunisia (Ben-Salem et al. 2006; Fouzai et al. 2018). While several studies identified the high cost of no-till seed drills as a constraint in the southern Mediterranean countries, this does not explain the low uptake in countries such as Spain and Turkey, where these tools are more widely available. Similarly, while government subsidies for wheat and barley and the unavailability of forage legume seeds and inputs may impede application of diverse rotations in Morocco and Tunisia, in Spain and Turkey, not only are inputs and seeds readily available, but some regional governments support CA through incentive programs. Considering that most of the tools and resources to implement CA are in place in the North, the main obstacles appear to include intellectual and cultural misconceptions on soil management, as well as potential disregard for the contextual circumstances of smallholders in the Mediterranean.

4 Five pathways for pragmatic CA adoption in the Mediterranean

Our review of constraints points to five pathways that could promote CA adoption in the Mediterranean across two main areas: (i) introduction of flexible, context-specific technical solutions and (ii) change of social perceptions and literacy on soil (Figure 3). These pathways were derived from the principles of agroecology (Wezel et al. 2020) as well as the authors' experiences in the region (CA based research and development projects such as ACIAR-AusAID, ACIAR-ICARDA, ACIAR-CAMA and CLCA IFAD). For instance, the two pathways under the "socio-ecological tools" are derived from Agroecological Principles 8 (co-creation of

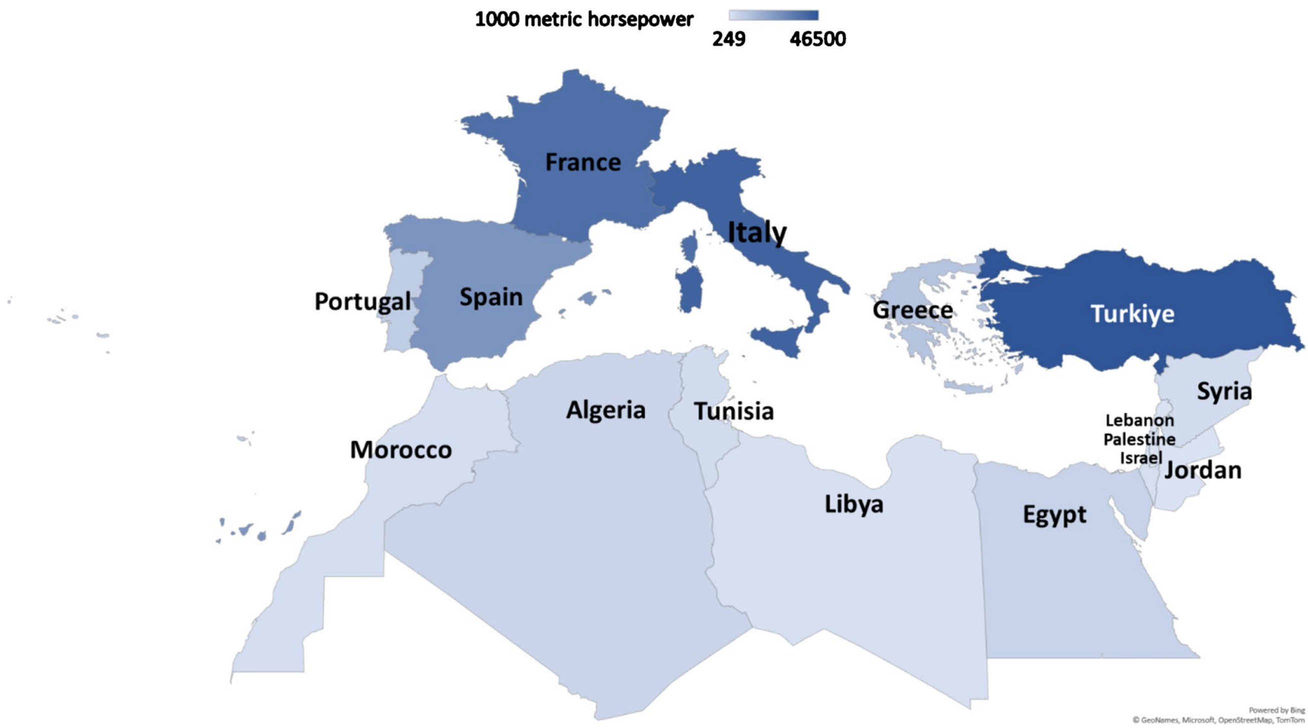

Figure 2 Total agricultural machinery stock (1000 metric horsepower) in some Mediterranean countries in 2020 (ERS USDA 2023). The per hectare or per farm metric horsepower calculation was not possible due to unavailability data on total cultivated land or total number of farms.

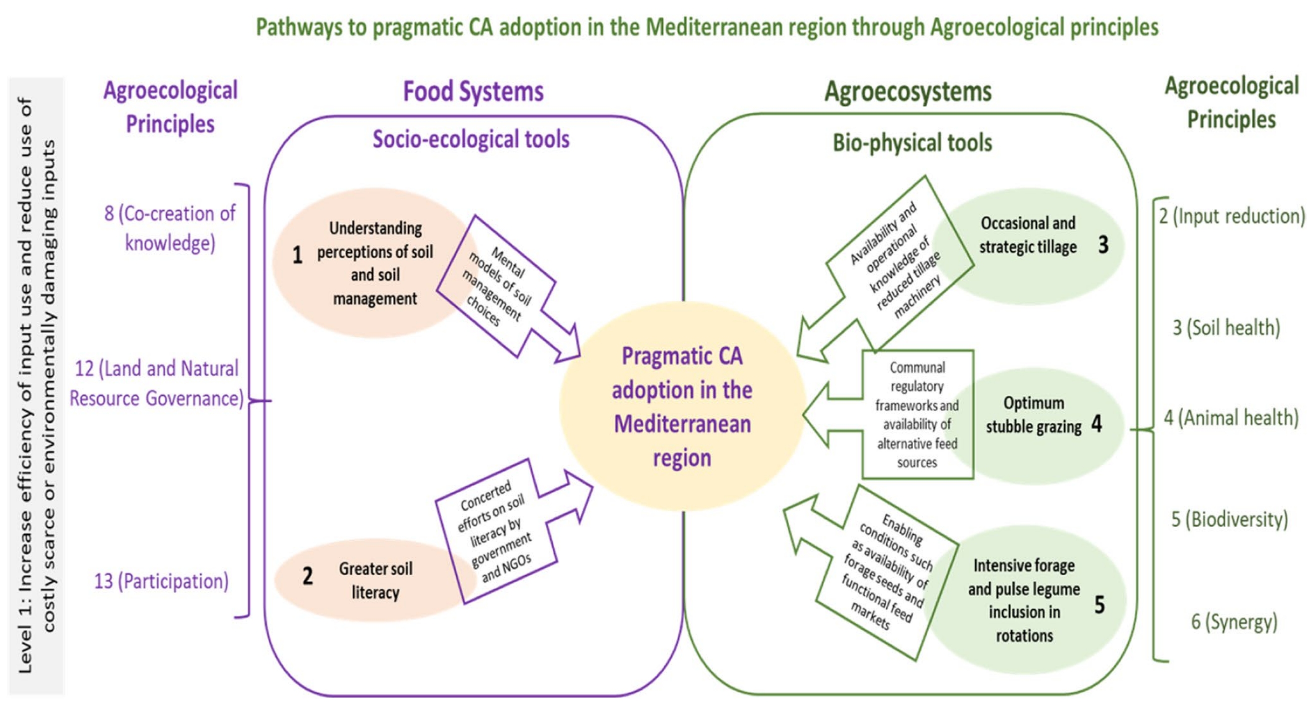

Figure 3 Five pathways to achieve pragmatic CA adoption in the Mediterranean region based on the 13 Agroecological principles defined by Wezel et al. (2020).

knowledge), 12 (Land and Natural Resource Governance) and 13 (Participation). The pathways listed under "Bio-physical tools" were derived from Agroecological Principles 2 to 6, which are explained below in relevant sections. Future CA themed research and development interventions in the region should first analyse and map the mental and cultural attitudes towards soil and its management, while simultaneously using educational tools (i.e. rainwater simulator) to improve farmers' appreciation and understanding of soils. Selected pragmatic application of CA principles then (e.g. strategic and reduced tillage, appropriate stubble grazing) should be investigated through on-station and on-farm experiments including farmers and other stakeholders, adopting a more pragmatic and ecological approach to CA based on site-specific bio-physical and socio-economic, cultural and mental factor considerations.

4.1 Pathway 1: Farmers' perception of soil and soil management

The agroecological principle of "Participation" emphasizes local adaptive management of agricultural and food systems through encouragement of greater participation in decision-making. How farmers understand the land and perceive soil degradation influences how they interpret this phenomenon, what attitude they adopt towards it and how they ultimately decide to act and develop land management (Prager et al. 2011). Applying a socio-cultural valuation towards land management practices enables understanding of farmers' decision-making with regard to soil management, by linking their perceptions, values, attitudes and beliefs with behaviour. Socio-cultural approaches applied in previous studies have shown the importance of considering multiple factors (i.e. economic, social and cultural) to identify motivations, perceptions and arguments regarding sustainability (Soriano et al. 2018; Costantini et al. 2020). Researchers often address socio-economic drivers of soil degradation but rarely investigate the psychological underpinnings driving farmers' soil management decisions. Documenting mental models can enable insight into farmers' perceptions of agroecological practices (van Hulst et al. 2020), landscape and farming practices (Vuillot et al. 2016), climate change and adaptation (Hitayezu et al. 2017) and tillage and CA (Halbrendt et al. 2014; Prager and Curfs 2016).

Conversion from tillage to no-tillage agriculture is a radical transformation that necessitates alterations in farm equipment, work organization, concepts of agriculture and personal and professional identities (Schneider et al. 2010; Peigné et al. 2016). There is a need to recognize and support of family farmers and smallholders as sustainable managers of natural and genetic resources (agroecological principle 13 "land and natural resource governance"). Lalani et al. (2016) found that the strongest predictor of intention to use CA was the attitude that farmers held towards CA. Among the factors driving the refusal of no-tillage or reduced tillage practices are the rooted beliefs, attitudes and social perceptions of farmers (Sattler and Nagel 2010; Schneider et al. 2012; Casagrande et al. 2016). Consequently, by switching to soil conservation measures such as no-tillage, farmers have to alter not only the routines of their daily farming life, but also their perception of the aesthetics of cultivated land, underlying values and images of themselves.

Mental models research offers a suite of methods that can be used to reveal these perceptions and how they might affect conservation outcomes (Moon et al. 2019). The analysis of mental models can allow better understanding of why farmers adopt or reject soil conservation measures, with a view to identifying basic dimensions to be covered in social learning processes in agricultural soil protection (case study 1). Additionally, practices that are perceived as soil management by researchers may not even be considered as such by farmers. For instance, Prager and Curfs (2016) revealed that tillage was not perceived as a soil management by farmers in southwestern Spain. Farmers used tillage to control the spread of shrubs, to eliminate competition for nutrients and water by weeds and to maintain "clean land" in their olive orchards. This implies that farmers either have very limited understanding regarding the effect of tillage on soil properties or do not perceive tillage as something that can degrade the soils. Contrary to scientific evidence, beliefs about the benefits of tillage for water availability and yield persist among the Mediterranean farmers (Topp et al. 2023). Improving soil literacy of farmers may lead to better understanding of soil as a valuable resource and soil degradation as a threat to their livelihoods (Montgomery 2007; Lalani et al. 2016).

4.1.1 Case study 1: Co-creating mental models of Mediterranean CA with pioneer farmers

Building on the agroecological principles of co-creation of knowledge, land and natural resource governance and participation, we documented co-constructed mental models of pioneer CA farmers in cereal-producing regions of Morocco, Spain and Tunisia. The aim was to shed light on the factors behind farmers' decisions to implement CA and to demonstrate workable examples for other farmers.

Workshops with six to ten pioneer farmers were held in the study regions from October 202 to February 2023 (Figure 4). The workshops followed a structured protocol of questions relating to motivations, benefits, drawbacks and overcoming problems related to CA implementation (van Hulst et al. 2020). The factors identified were subject to open discussion, allowing for shared insights. The cost-saving benefits of direct seeding on fuel, labour and time spent on tilling were a motivator shared by farmers across countries, while differences between the countries were also apparent. For example, in Morocco, some farmers also operate as service providers, performing tillage, seeding and harvesting for other farmers. In an illustration of pragmatism, these farmers continued to provide tillage operations for others, while they would practice direct seeding on their own land

Figure 4 Farmers and researchers in a mental models workshop, Meknes, Morocco, Oct 2022. Source: Najib El Hantaoui.

to save time. Strict adherence to a principle was thus not a motivator for CA uptake, nor were environmental and long-term benefits, such as increased soil fertility.

The farmer engagement through these mental modelling workshops can demonstrate the roles farmers have for diffusion of CA through the wider farming population (Padel 2001; Rogers 2010). Some were clear "pioneers" or innovators, who were closely aligned with scientific research institutes, and may have spent time overseas studying agriculture. Fellow participating farmers could be said to be pragmatic early adopters and viewed the pioneers as mentors or teachers. These exercises can serve as valuable activities in themselves for farmers to exchange and inspire experimentation, as well as inform research into adoption and societal transformation towards sustainability (Wittman et al. 2017).

4.2 Pathway 2: Increasing soil literacy

Social learning (among other forms of deliberation) can promote the change of values (Rodela et al. 2017) but the effects of ecological information on value shifts are rarely tested using an experimental design (Raymond and Kenter 2016). A stepwise approach that builds upon a solid understanding and appreciation of soil as a vital reserve that production is founded upon is the key. The following and parallel steps can involve innovative field demonstrations and scale-appropriate on station trials. Agroecological principle 8 "co-creation of knowledge" promotes enhancing co-creation and horizontal sharing of knowledge including local and scientific innovation, especially through farmer-to-farmer exchange. Farmer Field Schools (FFS) improve farmers' appreciation of soils and introduce them to concept of soil conservation with illustrated activities. Farmers have a substantially more positive attitude towards CA when they are involved in FFS (Lalani et al. 2016). FFS can be set up in selected farmers' fields and can be conducted as soil fairs, managed by national NGOs and farmers' associations.

In general, FFS are designed based on crop production, yet in the Mediterranean region soil literacy may be more important foundational training. There is a need to broaden the knowledge base and appreciation of farmers' perception towards soil and its conservation. Without the basic understanding of soil as a living entity and a vital resource, farmers cannot be expected to practice soil conservation. Improved knowledge on basic soil ecology will encourage farmers to increase their investments in soil conservation. Unlike the past attempts that focused on the technology itself, farmers and their perceptions on soil should be put in the centre stage. Illustrating soil processes using tools such as rainfall simulators are effective methods that comparatively illustrate the soil erosion mechanisms under different soil management options (case study 2). Benefits of stubble retention and soil cover are most effectively conveyed to farmers using such tools, but the effectiveness of such approaches is rarely documented in scientific literature.

4.2.1 Case study 2: Using rainfall simulators to improve farmers' understanding of soil-water nexus

Rainwater simulators can clearly demonstrate the responses of different types of soil management (tilled, no-till, with and without stubble cover, pasture etc.) on water capture, runoff, erosion, water storage and holding capacity (Figure 5). Buckets collecting the runoff and infiltration waters illustrate the capacity, or the lack thereof, of the soils to capture and store rainwater. In general, soils that have been under no-till and have stubble cover capture more water and lose less water through runoff. The appreciation of farmers on water capturing and conserving soil management techniques can be increased through such demonstration events. Our preliminary analysis indicates that a large number of farmers consider tillage as beneficial practice in order to capture and store water. Rainwater simulators can help in dispersing such beliefs. Potential changes in farmers' perception towards soil management due to FFS activities are being monitored and will provide important clues on upscaling CA across the region.

4.3 Pathway 3: Occasional or strategic tillage

The concept of no-tillage or zero soil disturbance is the most fundamental, yet least acceptable aspect of CA for farmers (Schneider et al. 2010). Tillage is a central feature of agriculture for Mediterranean farming systems and symbolizes ownership and management of resources. Besides its psychological underpinnings, tillage is the single most effective

Figure 5 Rainwater simulator developed by INRA is being tested before the Farmer Field Schools (FFS) in Settat, Morocco. Source: Harun Cicek.

tool for weed control and N mineralization for smallholder farmers (Kettler et al. 2000; Mazzoncini et al. 2016). As such, strict promotion of CA principles such as no-tillage is at odds with the realities of the Mediterranean agriculture.

Introducing occasional, strategic and reduced tillage as a scale-appropriate, pragmatic tool to manage weeds and favour N mineralization within the context of CA may facilitate greater adoption of CA. Such an approach also facilitates the Input reduction (agroecological principle 2) as the reliance on herbicides and fertilizers can potentially be reduced. Some soil disturbance may be necessary under several situations in the Mediterranean region. For instance, no-till pulse production is practically impossible in the southern Mediterranean countries due to the lack of post-emergence herbicides. Diversified rotations with forage mixes that suppress weeds and in-row soil cultivation are some of the few options for farmers who are wishing to grow pulses. When farmers rely on alternative weed management options such as forages, soil health (agroecological principle 3) can also be enhanced (Drinkwater et al. 2000; Entz et al. 2002). Also, in situations where high intensity stubble grazing leaves soil barren and compacted, the need for a slight soil disturbance becomes more evident (Bell et al. 2011; Telles et al. 2022). Occasional or strategic tillage can be used to disrupt disease and pest cycles, mechanically kill weeds, deal with herbicide resistant weeds or encourage weed seeds to germinate before a pre-season weed management operation (whether herbicide based or not) to make it more effective (case study 3) (Kirkegaard et al. 2014; Dang et al. 2018). Tillage can be aimed at improving soil structure and water infiltration or incorporate organic matter—such as crop residue or livestock manure—into the soil to optimize the availability of the nutrients for crop development (Reichert et al. 2017; Celik et al. 2019; Scanlan and Davies 2019).

Recently, a number of researchers have been questioning the strict adherence to no-till principles and displaying the positive effects of strategic tillage (ST) practices under various scenarios and soil types (Kirkegaard et al. 2014; Reichert et al. 2017; Dang et al. 2018). More than a decade of research in reduced tillage in organic agriculture has shown that shallow inversion tillage systems could accumulate more C and have negligible yield reductions compared to deep inversion tillage (Cooper et al. 2016), indicating that complete suppression of tillage may not be needed to achieve some of its purported benefits. Crucially, for the Mediterranean, there is a growing body of literature illustrating that reduced tillage systems may capture and store more water (Kribaa et al. 2001; Fellahi et al. 2013; Chennafi et al. 2016; Amami et al. 2021), reduce soil compaction and improve seed emergence (López-Garrido et al. 2014; Garcia-Franco et al. 2015; Amami et al. 2021) as well as improve yields (Seddaiu et al. 2016; Peixoto et al. 2020) than strict no-till systems.

4.3.1 Case study 3: Impact of occasional/strategic tillage on soil quality and crop productivity

Weed control in pulse production is the most critical area for strategic tillage in the project countries. However, farmers are also concerned about the negative effects that a one-time tillage operation may have on the benefits built after years of NT (Figure 6). Several on-station and on-farm experiments were established investigating the impact of some tillage options compared to no-till on weed management and crop productivity as well as on soil properties:

– Reduced tillage (disc harrow and non-intensive vertical tillage, e.g. chisel and cultivator) before sowing chickpeas, wheat and barley.
– In-row tillage during the growth of chickpea and faba bean

The results from these experiments will reveal whether these different tillage options are effective tools for controlling weeds and can replace the need for herbicides without negatively affecting crop production. The results will also enhance our understanding on whether such tillage operations have any negative impact on soil quality over the course of the project.

Figure 6 A one-time tillage operation on a long-term (12 years) no-till field in Meknes Morocco. Source: Harun Cicek.

There are also serious challenges to the claims of soil carbon sequestration and soil biodiversity improvements by CA (Giller et al. 2015; Garcia-Franco et al. 2015; Frøslev et al. 2022). It is clear that even in countries with larger mechanized farms, CA is applied with pragmatism, where occasional tillage is perceived as a necessary tool to manage variety of problems either built up by long-term no-till or caused by accidental mismanagement (Kirkegaard et al. 2014; Blanco-Canqui and Ruis 2018; Celik et al. 2019; Peixoto et al. 2020). Further research is needed to determine the critical aspects of the best timing, frequency and types of implement for tillage operations under local soil and agroclimatic conditions. Different approaches can be developed that consider the optimization of crop residue mineralization, water availability at sowing time and decreased risk of weed infestation.

4.4 Pathway 4: Livestock integration

One of the major factors that explain the lack of adoption of CA in Mediterranean cropping systems is the grazing of crop residues by livestock. Agroecological principle 5 (biodiversity) promotes maintaining and enhancing diversity of species and overall agroecosystem biodiversity in time and space at field, farm and landscape scales. In Mediterranean farming systems, crop residues traditionally are to be "shared" between soil and animals, but this practice clashes with the full stubble retention principle of CA. When promoting CA, many organizations advice farmers to retain stubbles. However, this is rarely taken up by farmers because harvested lands in many parts of the Mediterranean are considered as openly accessible, so that smallholder landowners have no control over the transient herds grazing their stubbles. Additionally, livestock is considered as more secure investment than crops for drought years (Koudrim and Hilali 2020).

Farmers often assume that without full stubble retention, direct seeding or CA cannot be practiced. Researchers, on the other hand, believe that stubble grazing is detrimental for soil quality and crop productivity. Indeed, stubble grazing practices in the Mediterranean region often lean towards intensive, high stocking rate methods that leave the soil barren, with damaged soil structure, compaction and diminished capacity to capture rainwater (Bell et al. 2011). Farmers often experience yield reduction, weed pressure and difficulty in seeding operations when converting their intensively grazed lands to CA. Although past experience indicates that a certain amount (i.e. ~1000 kg ha^{-1} or 30% of soil cover) of stubble must be present to achieve CA benefits, there is no empirical data from livestock integrated CA systems (Fisher et al. 2012). Most of the data comes from systems where full stubble retention is possible and little or no livestock pressure exists (Govaerts et al. 2005). Moderate stubble grazing may not be detrimental and could even be considered as a beneficial practice controlling pests and diseases and perhaps increasing soil organic matter (Hatfield et al. 2007; Stavi et al. 2015; Allan et al. 2016). As such, agroecological principle 6 (synergy) is clearly manifested in Mediterranean cropping systems through stubble grazing where livestock enhance positive ecological interaction among the different elements. Stubble grazing also in line with agroecological principle 4 (animal health) promotes animal health and welfare.

The reality of stubble grazing in the Mediterranean region necessitates an alternative approach and a need to establish optimal stubble management options under CA. First, there is a need to establish the optimum stubble amount and grazing intensity for optimum crop production and soil quality (case study 4). Then, there is a need to investigate whether a full or partial residue retention is economically and practically feasible for farmers who aspire to practice CA. For instance, recent rare research suggests that despite farmers' perception to the contrary, partial or full residue retention can be economically favourable because value of the additional grain yield offsets the cost of purchasing an equivalent amount of feed (El-Shater and Yigezu 2021). However, enforcing moderate grazing on lands that are considered as common property after harvest is a challenging task. When the amount of stubble available for grazing is constrained through restricted access to property, CA adoption becomes costlier due to reduced availability and higher cost of feed (Magnan 2015).

4.4.1 Case study 4: Impact of stubble grazing intensity levels on soil quality and crop productivity

There are no guidelines in the southern Mediterranean on grazing intensity of crop stubbles. It is important to understand the impact of various grazing intensity levels on soil and crop productivity. With this objective in mind, fenced plots with cereal stubbles are being grazed using different sheep numbers (intensity) and compared to non-grazed stubble plots (Figure 7). Results from these experiments will enable the researchers to recommend appropriate grazing intensities based on their contexts. The figure shows the stubble levels after two different stubble grazing treatments in Oued Zem Morocco.

Although crop residues are perceived to be the essential feed source during the summer months, the dry matter intake and nutritional quality of the stubble decrease linearly with an increasing number of grazing days and stocking rates (Treacher et al. 1996; Moujahed et al. 2015). Immediately after harvest, higher quality plant parts such as leaves and some grain are inadvertently left on the field. These higher quality materials have been shown to benefit livestock in live-weight gain, but animals consume these materials in just few weeks depending on the stocking rate (Ben Salem and Smith 2008). Another aspect of crop-livestock systems is the impact of faeces and urine on the following crop. The nutrient input through faeces and urine of grazing animals may be an important factor when evaluating stubble grazing (Schlecht et al. 1998; Sainju et al. 2011; Cicek et al. 2014). Moderate stubble grazing in CA systems can only be possible with the availability of alternative feed sources, such as mixes including forage legumes (El-Shater and Yigezu 2021). Reducing the pressure on stubble through production of forages may facilitate faster and more successful adoption of CA in the Mediterranean basin.

4.5 Pathway 5: Food and forage legumes

Food and forage legumes are perhaps one of the most prolific tools for application and achievement of many of the agroecological principles ((1) recycling, (2) input reduction, (3) soil health, (4) animal health, (5) biodiversity, (6) synergy and (7) economic diversification) (Wezel et al. 2020). Although diversifying cropping systems with legumes is the key to reverse land degradation and to enhance system productivity, profitability, nutritional quality and environmental health, legumes are often excluded from farming systems (Davis et al. 2012; Gan et al. 2015). As such, cereals have become the foundational element in the Mediterranean food pyramid, covering around 30 % of all Mediterranean arable land and representing up to 70% of caloric intake for low-income families in the region (Santos and Ceccacci 2015; El-Gharras et al. 2017; Royo et al. 2017). The underlying reasons for a reduction in legume cropping are diverse, ranging from improper agricultural policies supporting monoculture cereal production, agronomic challenges, and to socio-cultural and economic aspects (Zander et al. 2016; Foyer et al. 2016). Decades of unsustainable wheat monoculture practices have caused soil depletion, malnutrition and loss of diverse agronomic knowledge. Consequently, labour availability and the seed systems that can support legume cultivation have also been damaged.

Figure 7 Fenced experimental farmer's field with grazed (right) and ungrazed fields (left) with wheat stubble in Oued Zem Morocco. Source: Harun Cicek.

There are different challenges for pulse and forage legume cultivation. Agronomic factors such as poor competitive ability of legumes against weeds, unavailability of productive, locally available suitable legume seeds, susceptibility to diseases, and technical difficulties with harvesting are common for both group (Siddique et al. 2012; Watson et al. 2017). Even in major legume-producing countries such as Canada and Australia, issues relating to agronomic management of legumes rank as the most important research priorities in surveys of organic or low input farmers (Snyder and Spaner 2010). Most research on Mediterranean legume cultivation have been done under conventional systems where input availability (imported varieties, selective herbicides and advanced harvesters) is not a limiting factor, as is the case for the smallholders in the Mediterranean (Siddique et al. 2012; Christiansen et al. 2015). As such, scarce technical knowledge produced through these experiments on legume cultivation have little relevance and transferability for Mediterranean low-input smallholder farmers. Pulse production is labour intensive and requires high level of knowhow especially under low input conditions. Further lack of forage markets and untimely cash returns on forages reduce their attractiveness to farmers. There is an urgent need to produce novel knowledge on management options of pulses and forages under reduced and no-till tillage conditions for improved weed control and soil quality benefits (Rühlemann and Schmidtke 2015; Rusinamhodzi 2020). Neglecting legume inclusion in farming systems is directly responsible for scarce adoption of agroecological production systems that can preserve agroecosystem integrity and services (Vanlauwe et al. 2019).

Weeds are a major constraint for legume production in both mechanized high input farming systems in advanced countries and smallholders in developing countries. The widespread evolution of herbicide-resistant weeds (e.g. *Lolium perenne* (ryegrass), *Avena fatua* (wild oat) and the herbicide contamination of the environment is constraining legume production in developing countries (Valverde 2003; Peterson et al. 2018; Torra et al. 2022). For instance, the total area cultivated with *Lupinus* spp. in Australia decreased almost 3 times (from 1.4 M ha in 1999 to 0.5 M ha in 2008) mainly because weeds are becoming more difficult to control (Western Australia Agriculture). Under this scenario, more knowledge is needed to improve legume cultivation under limited or no herbicide use, which is specially challenging in reduced and no-till systems, due to the higher weed infestation compared to tilled systems.

Including annual and short-term perennial forages into rotations will greatly improve the possibility of adoption of CA because of the ability of forages to reduce weed pressure, improve soil fertility and soil structure and reduce the competition for biomass between the animals and soils, especially during summer period (grazing of the residue and soil cover) (Melis et al. 2016; Cicek et al. 2020). Additional advantage of short-term perennials is the fact that soil is not disturbed during the lifetime of the perennial plant (case study 5). This not only improves soil health, but also reduces the operational cost associated with tillage and seeding. With changing climate and increased occurrence of prolonged drought periods, the need for drought tolerant cropping systems becomes more imperative in the Mediterranean region. Practically, forage legumes are an easier choice for farmers than food legumes, because they require no external inputs (fertilizers or herbicides) and labour to manage weeds (Christiansen et al. 2015). However, there are serious issues surrounding the forage seed supply systems. The last several decades of focus on monoculture grains have depleted the forage legume seed diversity and value chains. There are some recent small public and also private initiatives that are trying to revive forage legume seed systems.

4.5.1 Case study 5: Investigation of short-term perennial forage legume inclusion

Sainfoin (*Onobrychis viciifolia* Scop.) and alfalfa (*Medicago sativa* L.) are promising short-term perennial forage legumes for Mediterranean CA systems. Main problem with the sainfoin is the low biomass productivity during the first year. To compensate for the low productivity, several nurse crops (seeded in mixtures with sainfoin) are being investigated. The advantage of these systems is that no soil disturbance is needed before or after sainfoin. Similar approach is also tested for alfalfa in Spain. In Tunisia, however, African alfalfa with winter dormancy is used as a cover crop, and oat is directly seeded into dormant alfalfa. The results from these studies will provide information on whether these short-term perennials can help in weed control and also improve soil quality and crop productivity. Along with the annual forages (preferably mixtures of legumes and grasses), short-term perennial forage legumes are one of the most critical tools to control weeds without resorting to soil disturbance.

5 Conclusions

Overview of the Mediterranean agricultural context for CA presented in this review showed that the small farm size and the resulting low ownership of agricultural machinery (i.e. no-till seeders) are strong drivers but do not completely explain the low CA adoption in the region. Intellectual and cultural misconceptions on soil management, as well as potential disregard for the contextual circumstances of smallholders in the Mediterranean when promoting CA, appeared as prominent causes. Five suggested pathways presented in this review directly addressed these two main areas of constraints (i.e. social and technical/contextual) and provided applicable and relevant action points for researchers and development professionals. In summary, we illustrated that agroecological principles 8 (co-creation of knowledge), 12 (land and natural resource governance) and 13 (participation) can be the guiding principles for the two "socio-ecological pathways" for pragmatic CA. We also found that agroecological principles 2 to 6 (input reduction, soil health, animal health, biodiversity and synergy) were the key principles for the three "bio-physical pathways" that can facilitate flexible CA application.

As explored in our research, many farmers select and apply various farming system principles according to their own experience and conditions, rather than adhering to a strict philosophy. The future of sustainable farming lies in harnessing the synergies among these farming systems and co-creation of soil management options that are in agreement with environment and socio-economic realities. Engagement with CA practices can be a "bridging concept" towards more landscape stewardship perspectives (Lavoie and Wardropper 2021). Agroecological farming may involve some acceptance of landscape heterogeneity and "messiness" that may also be at odds with farmers' preferences for tidy landscapes (Burton et al. 2008). Reconciling these different approaches involves acceptance of plural farmer identities and finding space in CA for farmers to exhibit a range of ways to be a "good" farmer.

In the Mediterranean region, farmers could be in the forefront of testing these flexible and innovative approaches, not only because of their central geographical location (between leading-edge and emerging economies), but also as a model region that is expected to be disproportionately affected by climate change. Outcomes from the mutual learning of these systems could offer new opportunities to farmers in the Mediterranean and the world. Our five pathways aim to enhance farmers' resilience to challenges of climate and market shocks, while integrating principles that enhance ecosystem multifunctionality. We advocate that a more pragmatic application of CA principles presents a great opportunity to rehabilitate degraded lands, to increase water use efficiency, and to improve food security and economic well-being of communities in the Mediterranean region.

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