1. General introduction

Cover crops are cultivated during the bare soil period between the harvest of a cash crop and the sowing of the next one (Justes, 2017). Cover crops cultivation puts into effect the permanent soil organic cover principle of conservation agriculture (FAO, 2016) and exerts several agro-ecological services, among which the most relevant are nitrate leaching reduction, weed growth control, soil organic matter increase, soil structure and water infiltration improvement. A meta-analysis reported a 70% nitrate leaching reduction obtained by replacing bare fallow with non-leguminous cover crops, while the reduction decreased to 40% in legume-fertilized systems (Tonitto et al., 2006). Cover crop cultivation ensures weed species growth control by reducing both weed biomass (mean difference of -42 g m^{-2}) and weed density (-6.5 plants m^{-2}), in comparison with the control, as reported by a meta-analysis (Osipitan et al., 2018). The soil organic matter increase deriving from cover crop cultivation is reported by a meta-analysis (Poeplau and Don, 2015) and corresponds to a mean annual carbon sequestration rate of 0.32 Mg ha^{-1} y^{-1} in comparison to fallow winter. Soil health indicators were found to be improved under cover crop cultivation in comparison to the control in a recent meta-analysis (Wood and Bowman, 2021): active carbon (+2.2 ppm y^{-1}), aggregate stability (+1.02% y^{-1}) and soil organic matter (+0.01% y^{-1}). Cover crop effects on cash crop yield are annually variable and possibly delayed (Chim et al., 2022). A meta-analysis reported that non-leguminous cover crop effect on cash crop (under suggested nitrogen fertilisation) is neutral thus not causing yield decline in comparison with the bare soil control, while a 10% yield reduction is observed when leguminous cover crop supply less than 110 kg N ha^{-1} (Tonitto et al., 2006).

Cover crop management involves essentially crop sowing and destruction (i.e. termination). Cover crop termination, generally carried out before or during seed bed preparation for the following cash crop, is the operation that kills the cover crop and prevents its growth from continuing during the cash crop growing season. In temperate climates when crop rotations include summer cash crops (such as maize or soybean), autumn-winter cover crops are sown between late July and October and terminated from March to April of the following year. Termination timing is influenced by the combination of following cash crop species sowing time-frame, farm location (that conditions climate), weather variability and applied termination method

(Justes, 2017). It can be performed mechanically by disking, ploughing or roller-crimping (Creamer and Dabney, 2002), or chemically through herbicide application (Pittman et al., 2020).

When sown in autumn, frost-sensitive cover crops may also be terminated efficiently by frost damage (Labreuche and Bodilis, 2010): this termination method is frequently called 'winterkill'. Since no direct economic benefit is expected for the farm from the cover crop biomass produced, which needs to be left in the field, its management is aimed at maximising agro-ecological services and at minimising cultivation costs. After termination or after winterkill, cover crop residues size and placement in the field depends on the termination method itself: in the case of winterkill, cover crop residues remain on the soil surface for relevant periods of time. In northern Italy, autumn-winter cover crops following or preceding a maize crop are frequently planted and terminated early (respectively during September and March) to obtain relevant cover crop growth during autumn. In this context, frost-sensitive cover crops are interesting because, if winterkill termination occurs, the seed bed preparation for maize is not delayed by cover crop termination operations. Furthermore, other positive aspects of winterkill termination occurrence, deriving from the non-execution of other termination operations, consist in cultivation costs savings (fuel, manpower and chemicals), avoidance of soil disturbance caused by tractor passes and of herbicides use (that may be harmful to humans and environment).

Black oat (*Avena strigosa* Schreb.) and white mustard (*Sinapis alba* L.) are two of the most interesting and widespread frost-sensitive cover crops due to their adaptability to various environmental conditions and cropping systems (Tadiello et al. 2022). Several studies focused on autumn-winter cover crop effect on nitrate leaching (Gaimaro et al., 2022; Justes et al., 2012; Meisinger et al., 1991; Storr et al., 2021; Tonitto et al., 2006) thus clarifying their contributions in terms of nitrogen uptake and nitrate leaching reduction. Therefore, cover crop cultivation effect on soil was deeply investigated with respect to nitrate leaching, while its effect on physical soil properties has been subjected to fewer studies. Several white mustard cover crop field trials performed in Italy (Campiglia et al., 2015; Mancinelli et al., 2015; Marinari et al., 2015) focused on the cover crop residue effect on soil quality, microbial function, weed control and cash crop yield in a cover crop- tomato rotation. A three-year field trial involving white mustard was also performed in Italy to assess cover crop cultivation effect on cash crop (maize and soybean) yield, as well as on soil nitrogen and organic matter pools in a no till cropping system (Fiorini et al., 2022). Furthermore, the work by Tadiello et al. (2022) focused on black oat and white mustard growth and agronomic effects in conservation agriculture cropping systems, where cover crops were cultivated in rotation with maize. These experiments, as much as they contribute to fill the knowledge gaps concerning these species, reported a limited number of measurements of cover crop aboveground biomass and soil mineral nitrogen, and there is still a lack of measurements of cover crop leaf area index, as well as of soil temperature and water content during their cultivation.

The results presented so far indicate that, although black oat and white mustard cultivation seems convenient, the information about these species used as cover crops under temperate climates is limited. The lack of information regards both crop management and agronomic effects, as well as winterkill termination occurrence frequency and efficiency. Since the possibility for a plant to be killed by frost depends on genotype, development stage and weather conditions (Janská et al., 2010), furthermore plant susceptibility to frost, in general, is lower during the earlier phenological stages and increases over time (Ambroise et al., 2020). Thus, the selection of the correct sowing time-frame plays a key role in determining winterkill success: it determines, together with temperature and photoperiod requirements, the development stage reached by the crop at the time of the exposure to the sub-zero temperatures. All these complex interactions, as well as those determining cover crop biomass productivity and agronomic effects, can be represented using a dynamic simulation model. Dynamic cropping systems simulation models can be used to determine crop management scenarios convenience for a wide range of weather and soil conditions, while the field trial assessments require large resource investments. Cover crop growth and development simulation will allow to support an informed choice of sowing and termination dates, as well as to evaluate their cultivation agronomic effects. These evaluation helps to analyse the consequence of the different management practises and can also drive the implementation of public policies. However, the application of a simulation model to white mustard and black oat cover crops presents several knowledge gaps, as the abovementioned limited number of studies focused on winterkilled cover crops agronomic effects carried out in northern Italy. Furthermore, an integrated simulation model dealing both with cover crop growth and winterkill termination, and its consequent effect on the crop-soil system including cover crop residue degradation on soil surface, is lacking.

Crop residue presence on soil surface has a relevant impact on many processes such as soil water dynamics, soil erosion (Dietrich et al., 2019) and biodiversity (Fiorini et al., 2020). Furthermore, superficial residue decomposition, even if this pool is characterized by slower decomposition rate compared to the ones incorporated into the soil (Douglas et al., 1980), has significant effects on nitrogen and organic carbon dynamics (Chaves et al., 2021; Coppens et al., 2007; Guérif et al., 2001; Iqbal et al., 2015; Robertson et al., 2015; Stella et al., 2019). Several cropping system models have been developed modules to simulate the decomposition of surface residues as influenced by agronomic management, soil and weather variability: WEPP model (Alberts et al., 1987), STICS model (Justes et al., 2009) and APSIM model (Thorburn et al., 2001). Each of these models differently focuses on specific biochemical or physical aspects of the degradation, as well as on different cropping system processes that are influenced by the degradation itself. Although C-oriented models (Bruun et al., 2006; Dietrich et al., 2017) do not simulate crop growth, as well as the effect of management operations on soil, they carry out a more detailed simulation of surface residue decomposition. Despite the richness of processes and the diversity of algorithms employed by both cropping system and C-oriented models, an approach with the right balance between complexity, completeness, and applicability in cropping system models for the simulation of surface residue decomposition is still missing.

On the other hand, few simulation models already simulate white mustard and black oat, among which the most widely used for both species is STICS, while HERMES model (Kersebaum, 2010) is less commonly used for white mustard. STICS was calibrated and validated using several databases (Constantin et al., 2015), including crop rotations with mustard, annual ryegrass (*Lolium multiflorum* L.) and common vetch (*Vicia sativa* L.). Then the model was applied in different climatic conditions in France, to evaluate the effect of sowing and termination date on nitrate leaching thus allowing the selection of the optimal dates for leaching reduction. Other few modelling approaches address cover crops simulation, but these two species are not parameterized yet: FASSET model (Doltra et al., 2019), DSSAT v4.7.0.001 model (Leuthold et al., 2021), DayCent model that is implemented in the decisions-support tool COMET-Farm (McClelland et al., 2021), PNM (precision nitrogen management) model (Melkonian et al., 2017). None of these models simulate winterkill event occurrence and the subsequent effects on the cropping systems.

ARMOSA (Perego et al., 2013) is a dynamic cropping system model, that simulates, at a daily time-step at field scale, crop development and growth, soil-plant-atmosphere water, and nitrogen dynamics. It has a modular structure that involves a micrometeorological model, a crop development and growth model, a soil water balance model and a soil N and carbon balance model. The crop module employs the following calculated variables: evapotranspiration, soil water content, soil nitrogen and carbon contents. The crop growth module is based on gross assimilation of carbon dioxide (CO_2), and estimates maintenance and growth respiration to obtain the final net carbon assimilation as implemented in SUCROS (van Keulen et al., 1982) and WOFOST models (van Keulen and Wolf, 1986). ARMOSA model simulates already a variety of cash crops among which grain and silage maize, winter wheat (*Triticum aestivum* L.) and annual ryegrass. The need of calibrating ARMOSA model to simulate white mustard and black oat growth, winterkill termination and residue degradation on soil surface has arisen from the urge of supporting cover crop management decision within the area of interest, that is characterised by high nitrogen surpluses that were reported by several previous studies.

For what concerns plants susceptibility to frost damage, plants can be divided into four frost sensitivity categories: tender; slightly hardy; moderately hardy; and very hardy (Levitt, 1980). Tender plants are those that do not develop systems of avoidance of intra-cellular freezing, while slightly hardy plants are sensitive to freezing down to about -5 °C. Moderately hardy plants include those that are able to accumulate sufficient solutes to avoid dehydration damage, thus resisting freeze injury at temperatures as low as -10 °C. Very hardy plants are the ones able to avoid frost damage even at temperatures lower than -10 °C through the avoidance of intracellular freezing as well as cell desiccation (Snyder and Melo-Abreu, 2005). The timing of phenological and physiological responses induced by low temperature stress is subject to strict genetic control (Guy, 1999). Therefore, the variability of tolerance expressed by a plant is determined firstly by genotype, and then by plant phenological stage and physiological conditions at the time of exposure. Furthermore, plant organs differ in their low-temperature tolerance potential: the crown, the meristematic tissue responsible for shoot and root production, has been found to be less sensitive than roots (McKersie and Leshem, 1994). To the best of our knowledge, existing cropping system models do not simulate the process of cover crop damage by winter frosts. An option to improve current models is to adapt to cover crops the modules available for the simulation of frost damage on annual crops: winter survival model (Byrns et al., 2020), FROSTOL model (Bergjord et al., 2008), the model proposed by Lecomte et al. (2003), ALFACOLD model (Kanneganti et al., 1998), CERES-Wheat model (Ritchie, 1991), EPIC model (Sharpley and Williams, 1990), APSIM-Wheat model (Zheng et al., 2015) and STICS model (Brisson et al., 2009). The most interesting models are the ones that simulate a crop frost tolerance temperature. The model proposed by Lecomte et al. (2003) estimates crop frost resistance on day *d* (R_d, °C), which is defined as the temperature below which the first leaf damage occurs, using air temperature as driving variable. FROSTOL and Byrns et al. (2020) simulate frost tolerance as the "lethal temperature 50" (LT_{50}, °C), which is defined as the soil temperature in the crown region at which 50% of the plants are killed in an artificial freeze test (Bergjord et al., 2008). In all these models, frost tolerance is increased by low temperature hardening (that decreases the frost tolerance temperature) and is lowered by de-hardening (that increases frost tolerance temperature). Assessing crop frost tolerance though the use of a simulation model enables to estimate crop winter survival and to identify the sowing date that, in each site, ensures the greatest chance of overwintering or winterkill. This is particularly important for cash crops cultivated in cold regions, where the risk of winterkill is higher than in temperate climates. Assessing the likelihood of crop overwintering or winterkilling in a specific region is also important for cover crops.

Cropping system models, surface residue decomposition algorithms and frost tolerance models employ several parameters that need to be calibrated, by adjusting their value, to obtain the best possible fit between simulated and measured values for the considered species. Calibrating many parameters requires extremely large data sets and can lead to the identification of local instead of optimal combinations of parameter values. Therefore, even in complex agronomic models, only few relevant parameters should be calibrated. These can be identified using sensitivity analysis, a statistical technique that assigns model output variability to different model input parameters (Saltelli, 2004). Sensitivity analysis is therefore needed for a more informed use of a model. It can be performed using local methods such as the one-factor-at-a-time (OAT) screening techniques, or global methods such as the one designed by (Morris, 1991) or the one developed by Sobol (Saltelli et al., 2010).

In conclusion, the identified knowledge gaps concern: (i) crop management and agronomic effects, as well as frequency and efficiency of winterkill termination, for frost sensitive cover crop species in northern Italy; (ii) an integrated simulation model dealing both with cover crop growth and winterkill termination, and the consequent effects on the crop-soil system, including cover crop residue degradation on soil surface. To fulfil the abovementioned knowledge gaps, a three-year field trial was performed to evaluate the agronomic performance and the effects of two frost-sensitive cover crops, white mustard and black oat. Data deriving from the field trial, together with previous experiments and literature data, were used to develop an integrated simulation model that will allow to support an informed choice of sowing and termination dates, as well as to evaluate cover crop agronomic effects.

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