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Sowing and seedbed management methods to improve establishment and yield of maize, rice and wheat across drought-prone regions: A review

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ABSTRACT

The quality of crop establishment is affected by several biotic and abiotic factors. The adverse impact of these factors can be mitigated through crop management practices. Development of practical management solutions may help farmers to reduce their production costs and thus increase yield. Here, we report practical and sustainable methods that aim at improving the establishment quality and yield of three key cereal crops viz. maize, rice and wheat, particularly suitable for drought-prone regions. We found that some new methods including printed sowing, variable-rate seeding, night-time sowing as well as other relatively old methods such as bed- and raised-bed sowing, mulching, incorporation of organic matters into the seedbed etc. allow to improve crop establishment and yield while increasing water use efficiency and reducing greenhouse gas emissions. However, there is no a 'one-size-fits-all' method to improve cereal crop establishment and that the potential adoption of such methods by farmers may be affected by a number of factors, including the farm size and the crop type. We highlight that the methods presented herein have been successfully tested only for maize, rice and wheat and across limited pedo-climatic conditions. Consequently, there is a knowledge gap about the potential of these methods to implement for a broader range of crops and cropping systems across drought-prone regions of the world. This will finally improve our understanding of the overall effectiveness of these methods in fostering crop establishment, early stand development and yield.

1. Introduction

Crop establishment consists of three sub-phases: sowing to seed germination, seed germination to seedling emergence, and seedling emergence to initial competition among young plants [1]. A high quality of crop establishment and subsequent crop stand development are key objectives for farmers to ensure a good crop productivity. Several biotic stresses such as soil-borne pathogens [2,3] and animal pests [4,5] attack seeds and seedlings both in pre- and post-emergence phase. Likewise, abiotic stresses such as drought [6] or mechanical obstacles including a soil surface crust [7] and soil clods can negatively affect the quality of field crop establishment with severe economic consequences for farmers.

More specifically to abiotic stresses, water stress represents the most important constraint for a successful crop establishment and subsequent crop performance across many regions of the world [6–9]. While drought represents the most important and frequent limiting factor for crop establishment and subsequent performance across semi-arid [10,11] and Mediterranean [12] regions, this stress has become increasingly frequent even across other regions of the world, especially under ongoing climate change. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change highlights that both quantity and quality of water will change across many parts of the world, in particular across semi-arid regions where the water availability depends on precipitation amounts and evaporation rates, that further restrict local water availability [13].

Seed technology has markedly improved in the last decades that have resulted in improved seed germination ability and seedling vigor even under high-risk drought conditions. A number of methods have been developed and used to alleviate the effect of drought stress including pre-sowing seed treatments such as hydro- [14] or osmo-priming [15] of seeds or post-sowing field inoculations with plant growth promoting rhizobacterial strains [16]. While all these technologies allow to improve seed germination and emergence rates, not all farmers benefit from these technologies due to their relatively high production costs. This is especially true for field crops such as cereals that are characterized by low profit margin. Therefore, low-cost seedbed preparation and sowing methods that improve seed germination, seedling emergence and stand

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development can result useful for field crop farmers across drought-prone regions. The quality of seedbed preparation may largely depend on a number of factors including cropping systems, soil texture, time of harvest and seedbed preparation and the type of machinery used for field operations [17,18].

The objective of this paper is to briefly highlight and discuss key methods that help improve the establishment quality and yield of three key cereals, viz. maize, rice and wheat, especially across drought-prone regions of the world with low annual or growing season rainfall. We focused only on these three crops as the methods reported in this paper have been successfully tested only for these cereals and especially across soil moisture limited conditions. To this aim, we used the following keywords for literature research alone or in combination: “precision sowing + emergence”, “precision sowing + water use efficiency”, “night-time sowing + emergence”, “biodegradable field mulching + emergence”, “sowing methods” “seedbed preparation”, “stand development” on Web of Science.

2. Sowing methods that help improve crop establishment and yield

Precision farming is modern concept for the precise management of water, seeds, fertilizers and other agricultural inputs as farmers can use precision technologies to know and manage the variations within their fields [19]. Key precision sowing methods useful in relation to crop establishment are discussed below.

2.1. Printed sowing

More specifically to precision sowing (also known as precision planting or prescribed farming), this technique allows to reduce seed rate per unit surface and labor costs thereby reducing production costs. Compared to high-value crops, such as vegetables or industrial crops, seed costs for field crops and especially for cereals are lower. However, seed costs may be an important issue when farmers use high quality certified seeds. An example is hybrid rice for which seeds costs represent an important production cost for farmers [20]. Therefore, it is important to reduce the seed rate used for this crop without affecting the crop productivity. In addition, for rice there is a need for an alternative crop establishment method that replaces manual transplanting with lower labor inputs. A recent study [21] from China showed that printed sowing, which consists in pasting seeds to paper, reducing the seed rate by up to 6% compared with manual sowing. Rice plots sown with this method provided higher seedling quality, larger panicle size, higher spikelet filling percentage, higher above-ground biomass, and higher harvest index compared with manually sown plots. This technique may result useful to a large number of farmers worldwide. This technique, especially when applied under rainfed cropping systems may significantly decrease production costs for farmers.

2.2. Variable-rate seeding

Variable-rate seeding is another method that has potential to reduce crop input costs in areas of low productivity and increase yields in areas of high productivity [22]. This is possible by optimizing seed inputs spatially by matching seeding rate with productivity zones within a field using a variable rate capable planter [23]. This method is particularly useful when variation within a given field is identified on various data layers such as historical emergence rates and stand development, yields, soil properties, topography and/or aerial imagery [24]. An example of a field with variation is that with summits and toe slopes. In such a case, the use of a lower seeding rate in the summits, with shallow soils (lower productivity area), and a higher rate in the toe slopes, with deeper soils (higher productivity area), would maximize grain yields while minimizing costs. The seeding rate however depends on crop species to be sown. Seeding rates for maize can be increased in high productivity zones and decreased in low productivity zones, while it may be the opposite for other crops. Allen [25] compared the productivity of different maize seeding rates across different sites with severe water deficit throughout a growing season with a different precipitation gradient in the Northern Great Plains (USA). The authors did not found a positive correlation between the seeding rate and grain yield.

Variable-rate seeding technology can also be combined with GPS-based precision irrigation system that enables farmers to apply water and other agriculture inputs more precisely and at desired position. All this finally improves the crop establishment, water use efficiency and crop productivity [26]. Prasad et al. [27] revealed that smart precision farming along with system model can predict the area best suited for particular crop plantation by analyzing the variations present within fields. Various modern approaches such as IRRISAT and Mod are employed for the saving of water under water limited areas [28]. Water electronics module is modern precision technique that can be used for the precise application of water under water deficit zones. For instance, this method resulted in 12–21.7% water saving in alfalfa under different field capacities [29]. Variable-rate seeded can be coupled with variation-rate irrigation that can reduce deep water percolation losses and conserve soil moisture within a particular field [30]. This finally helps increase the soil moisture within a field thereby improving crop establishment and productivity.

2.3. Night-time sowing

Across regions characterized by frequent dry and hot environmental conditions, night-time tillage and sowing can be a simple and effective agronomic practice to improve seed imbibition, germination and the subsequent emergence. Seedbed moisture is the most important limiting factor affecting crop emergence across these regions [31]. This is especially true when crops are sown in previously prepared seedbeds without the presence of crop residues on the soil surface and during the day in the presence of sunlight and high diurnal temperature and/or strong dry winds that lead to temporal moisture variation in near-surface conditions [32]. Water loss due to soil evaporation is higher in the upper soil horizon; the sowing depth of field crops generally ranges from 1 to 5 cm, depending on the seed size and sowing conditions [33]. In general, the mean seedbed temperatures are lower during the night compared with those of the day (Table 1), due to the absence of evaporation and soil desiccation. Under this condition, soil moisture during night-time in hot and dry periods may last relatively longer for almost 10–12 h. This provides opportunity for seeds to speed-up the seed imbibition process and foster germination and emergence rates.

Recently, Khan et al. [34] investigated the effectiveness of night-time sowing of maize hybrids on crop emergence and subsequent performance in an arid area of Pakistan. The authors showed that night-time tillage and sowing significantly reduced time to accomplish seed germination and seedling emergence and improved their final rates and crop yield, compared with day time tillage and sowing. Further studies are needed to confirm whether the effectiveness of night-time tillage and sowing on

Table 1
Mean day and night soil temperatures and moisture at different depths measured from 24th May to 20th June 2018 in a plot in Auzeville experimental site (43.53 °N, 1.58 °E), southwestern France (Source: Lamichhane et al. [57]).

Time	Mean soil moisture (%) ± SD			Mean soil temperature (°C) ± SD		
	−3 cm	−5 cm	−10 cm	−3 cm	−5 cm	−10 cm
Day	14 ± 3	19 ± 2	24 ± 1	25 ± 3	24 ± 3	23 ± 2
Night	13 ± 2	18 ± 2	24 ± 1	19 ± 1	19 ± 1	20 ± 1
Significance level	NS	NS	NS	***	***	***

SD: standard deviation, NS: not significant; ***$P < 0.001$.

crop establishment differ from one pedo-climatic conditions to another and among crop species. Moreover, more research is needed to pinpoint whether the effectiveness of night-time sowing is high independent of the type of tillage and if no-till attenuates the benefits of sowing during the night. In addition, limits of this method need to be assessed including the difficulty to work during night and the associated labour cost. No-till represents the best way to improve water use efficiency in arid or semi-arid regions, by reducing evaporation, especially when the soil is covered by mulch, compared with conventional tillage. In addition, weed infestation problem is better managed with tillage and farmers tend to practice tillage across these regions. Indeed, the benefits of photocontrol (i.e. weed control by night-time tillage) in reducing the emergence of different weed seeds requiring light for germination is another reason for farmers to perform night-time tillage [35]. Nevertheless, Juroszek et al. [36] suggested that the delayed soil desiccation process in night-time tilled plots may promote unexpected weed germination which may affect crop productivity. Therefore, the effect of night-time tillage and sowing on weed growth and their consequent impact on crop productivity need further attention.

The paucity of information in the literature does not allow us to understand whether there is a significant difference between the day and night-time soil moisture, during hot and dry growing seasons. Recently, we measured seedbed temperature and moisture at the −3, −5, and −10 cm soil horizon in a field site located in Auzeville (43.53 °N, 1.58 °E), Southwestern France, from late May to late June (Fig. 1). Our data suggest no statistically significant differences between the day and night soil moisture at these soil horizons (Table 1). In contrast, the average seedbed temperatures across these soil horizons during the day time were significantly higher than those registered during the night-time (Fig. 1). However, late spring season is not the hot and dry period of the year in Southwestern France or southern Europe in general. Therefore, the same variables of the seedbed weather should be measured during hot and dry periods of the year (i.e. summer) across these regions. The moisture level has been reported to affect seed reserve utilization and seedling growth in wheat [6] that may have an important impact on emergence of crops sown during summer across dry summer regions. Therefore, regions with hot and dry cropping seasons may benefit from either from no tillage at all or night-time tillage and sowing due to relatively higher soil moisture at the sowing depth compared with the day time. Across semi-arid regions, this might be due to dew formation and water vapor absorption [37] which would merit further investigation.

2.4. Bed and raised-bed sowing

Bed sowing of different crops showed significant results in terms of water saving under water limited areas. For instance, 42.6%, and 31.5% of water saving was recorded for wheat and rice, respectively, under bed sowing [38]. Razaq et al. [39] tested raised-bed wheat sowing and found maximum growth and yield parameters under semi-arid climatic conditions. Likewise, moisture conservation ranging from 23-29% was recorded in raised-bed planting of maize, especially under no-till compared with conventional system [40].

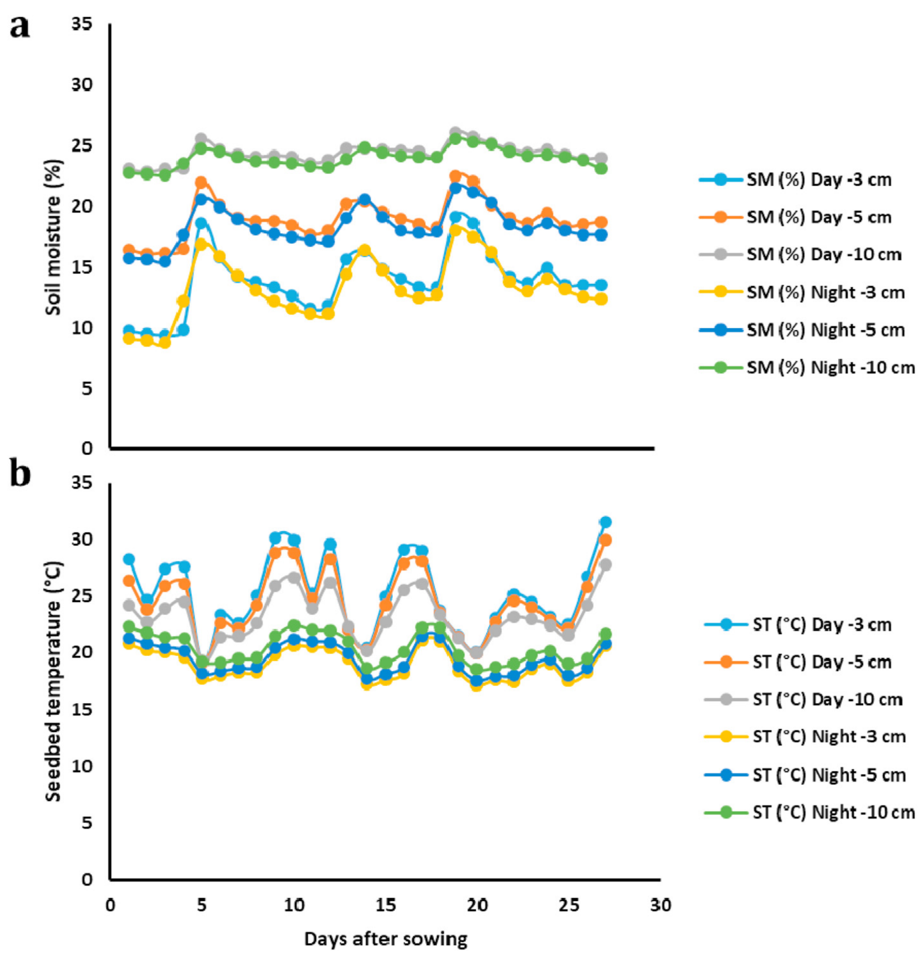

Fig. 1. Dynamic of mean seedbed moisture (a) and temperatures (b) at different soil depths during day and night time. The measurements were conducted from 24th May to 20th June 2018 in a plot sown in Auzeville experimental site (43.53 °N, 1.58 °E), southwestern France (Source: Lamichhane et al. [57]).

3. Mulching methods that help improve crop establishment and yield

3.1. Ridge–furrow with plastic film mulching

This method has been reported to provide several benefits compared with the conventional flat planting pattern. Examples include in maize [41], and winter wheat [42]. Ridge-furrow system, by collecting, runoff water in semi-arid areas, helps improve the water use efficiency, and crop yield (Table 2). This system requires adjusting the plant density, the distances between ridges and furrows, and their width for different crops. Li et al. [42] pointed out that winter wheat seedlings were established faster and more stable in ridge–furrow with plastic film mulching system than flat planting pattern, and a 40:20 ridge–to–furrow ratio had the highest crop yield and water use efficiency under rainfed conditions.

3.2. Biodegradable film mulching

In regions with relatively cheaper labor costs, mulching with films is an important agricultural practice most commonly used for several field crops including cereals in arid, semi-arid, and sub-humid areas, especially where irrigation is not available and spring temperatures are low [43,44]. This technique helps maintain seedbed moisture and increase seedbed temperature accelerating the seed germination and seedling emergence process with improved crop performance (Table 2). While mulching with plastic film is widely practiced by farmers across these regions, the use of this material is not practical for farmers as it requires removal after some period from the field with additional labor costs to bear for farmers. If not removed, the lack of biodegradability of this material leads to several negative environmental impact including greenhouse gas emissions [45]. In addition, the presence of plastic materials in the soil negatively affects soil health [46]. Therefore, replacing plastic films with biodegradable materials may result practical for farmers as it may provide the same benefit while eliminating drawbacks due to the use of plastic materials.

Table 2
Examples of sowing methods that increased crop emergence and final yield of cereal crops.

Method used	Crop	Increase in crop emergence (%)	Increase in crop yield (%)	Reference
Biodegradable film/straw	Maize	ND	31.77	[60]
	Maize	ND	27.49	[47]
	Maize	ND	9.18	[61]
	Maize	ND	32.19	[62]
	Maize	ND	27.09	[63]
	Maize	ND	20.93	[64]
	Maize	ND	6.88	[65]
	Maize	ND	13.58	[66]
	Maize	8.57	ND	[67]
	Wheat	ND	7.10	[65]
Plastic/ polyethylene film	Maize	ND	29.98	[69]
	Maize	ND	19.93	[65]
	Maize	ND	40.57	[60]
	Maize	ND	40.05	[62]
	Maize	ND	51.79	[63]
	Maize	ND	26.09	[66]
	Maize	ND	18.91	[64]
	Wheat	ND	24.39	[65]
Optimized planting pattern	Maize	ND	33.35	[68]
	Maize	ND	17.13	[41]
	Maize	ND	14.37	[69]
	Wheat	ND	2.28	[70]
	Wheat	ND	36.22	[42]
Precision planting	Maize	ND	6.80	[71]
	Rice	ND	25.67	[72]
	Wheat	ND	10.19	[73]
	Wheat	ND	4.84	[74]
	Wheat	ND	8.66	[71]
Planter attachment	Maize	15.82	ND	[75]
Printed sowing	Rice	ND	10.82	[21]

ND: not determined.

4. Incorporation of organic matters improving crop establishment and yield

4.1. Crop residues

Crop residues improve soil physical properties, control weeds and conserve soil moisture that finally improve crop establishment and yield performance (Table 2). For instance, wheat residues have increased improved water holding capacity, humus content of soil, increased the rainfall water infiltration and ultimately moisture conservation within soil [47]. In maize production, wheat residues proved to be beneficial in terms of improved water use efficiency and consequent crop productivity, under semi-arid climatic conditions [48]. Crop residue mulching retained 7.7% higher soil moisture content in wheat production under sandy loam soil [49].

Straw strips mulch on furrows is another innovative practice widely adopted in field crop productions across semi-arid regions of China. This technique improves soil moisture conservation, which is attributed to increased infiltration during heavy rains, decreased soil temperature and water evaporation from soil surface [50,51]. Seed germination is enhanced due to the presence of straw mulch on furrows providing optimal soil moisture required for seed imbibition. Finally, double blank row mulching has been reported to improve wheat growth and yield as it optimizes soil temperature and increases water content into the soil across water limited areas of northern China [51].

4.2. Farmyard and poultry manure

Besides crop residues, integration of farmyard manure into the seedbed is a sustainable practice that increases soil water-holding capacity with lower need for irrigation. For instance, the incorporation of manure into ridges and furrow planting systems increased the soil moisture content and, ultimately, maize productivity under semi-arid regions of China [52]. Farmyard manure (5 tha^{-1}) along with tied ridging improved maize crop stand and productivity in semi-arid regions of Eastern Kenya even under rainfed conditions [53].

5. Decision support tools and modeling that help improve crop establishment and yield

The sowing date is mainly dependent on air temperature, seedbed temperature, and moisture status, especially under rainfed conditions. An optimal planting date exposes the whole crop to the best environmental conditions across its growth phases and will eventually result in the highest crop yield. Because the sowing date mainly depends on these climatic variables, it may differ from year to year, especially under ongoing climate change. Thus, determination the best time for sowing is difficult to identify through field experiments that requires long-term experiments across several locations [54].

Crop models are important decision support tools to determine optimal sowing dates [54–59]. Adnan et al. [54] used CERES-maize crop model for optimizing sowing dates in Northern Nigeria and suggested the optimum sowing dates. For example, in the northern Guinea Savanna, the best planting dates were mid to late July to obtain the highest crop yield. Dobor et al. [55] applied 4M crop model to estimate optimal sowing dates for maize and winter wheat and showed that, due to climate change, sowing date of maize in future (2071–2100 period) shifts ~12 days earlier while planting date of winter wheat changes ~17 days later. All this shows the usefulness of crop models in decision making by farmers to adjust their crop managements based on weather forecast that finally help improve crop establishment and yield.

6. Conclusions and perspectives

The increasing need to improve crop productivity while reducing the negative environmental impact of agricultural practices calls for the development and testing of easy-to-use, environmental-friendly and cost-effective methods readily applicable by farmers. This paper summarizes both relatively old as well as new methods that have potential to improve establishment and yield performance of maize, rice and wheat across drought-prone regions of the world. However, the methods presented herein have been successfully tested only for these cereals, and across limited pedo-climatic conditions and cropping systems. Thus, there is further need to test these methods for a broader range of crops and cropping systems across drought-prone regions of the world. This is because every cropping system is different, and farmers have to adapt their agronomic practices not only based on their cropping systems but also on pedo-climatic conditions. This will finally improve our understanding of the overall effectiveness of these methods in fostering crop establishment, early stand development, and subsequent crop productivity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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