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Review

A comprehensive review of planting approaches used to establish willow for environmental applications

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ABSTRACT

Willow is considered an ideal plant species for environmental applications, including phytoremediation. Improving planting efficiency and reducing the costs of phytoremediation have become key steps for increasing its application. This paper reports the most update-to-date information on frequently used techniques for establishing willow, including plant material, planting methods, and the factors influencing the early establishment of trees in the field. The five main types of planting materials (rods, cuttings, billets, micro-cuttings and single-bud short branches), and the seven main planting techniques, especially different vertical and horizontal planting directions, were assessed. Factors affecting willow establishment were also reviewed, including the characteristics of planting materials (i.e., clones, cutting phenology, propagules size, pre-treatments), operation during planting (i.e., timing, orientation and planting depth) and post-planting management (i.e., soil conditions and weed management). New planting approaches with small-sized cuttings (of about 5 cm in length) have been recently proposed showing promising economical and effectiveness characteristics, especially for the establishment of willows in harsh soil and challenging conditions.

Phytoremediation is a sustainable remediation technology first introduced in the 1980s to remove toxic and harmful substances from the environment (Pulford and Watson, 2003; Hartley et al., 2011; Shang et al., 2020), and as a plant-based technology for ecological restoration of non-polluted environments (Teodorescu et al., 2011; Tognetti et al., 2013). Willows (*Salix* spp.), which show rapid growth rates, easy establishment, large root systems and biomass, high transpiration rate and strong adaptability to pollution, are considered ideal plant material for phytoremediation (Kuzovkina and Quigley, 2005; Teodorescu et al., 2011; Moreno et al., 2019; Desrochers et al., 2020). Together with vigorous growth and productivity, the rapid and extensive fine roots of willow crops can achieve high nutrient and pollution uptake (Cao et al., 2011), with yields on brownfields often reaching ~10 Mg ha^{-1} biomass per year (French et al., 2006). To date, willow has been widely used in the treatment of contaminated soil (Pitre et al., 2010), wastewater (Guidi Nissim et al., 2014), and landfill leachate (Guidi Nissim et al., 2021; Benoist et al., 2023), the restoration and construction of abandoned industrial and mining sites (Guidi Nissim et al., 2012; Fortin Faubert et al., 2021), buffers against wind (Kuzovkina and Quigley, 2005) and road noise (Tognetti et al., 2013; Heavey and Volk, 2014), as riparian buffer zones (Hénault-Ethier et al., 2017) and other habitats, providing a wide range of ecological and social benefits.

The main factor limiting large-scale establishment of plantations is economic: high infrastructural costs and a high initial investment required when planting woody crops (Sassner et al., 2008; Stephen et al., 2013). Planting on brownfields is usually performed manually due to harsh field conditions unsuitable for agricultural machinery, resulting in both high labor costs and risk of exposure to contamination for operators (Frenette-Dussault et al., 2019). In general, the establishment costs of willow plantations are divided into two parts: planting materials and on-site operations, accounting for 80% and 20%, respectively (Welc et al., 2017). However, the promotion and application of willow woody crops and energy forests is limited due to the high planting cost in the early stage (including the preparation of cuttings and the planting operation) (Bergante et al., 2016). According to estimates made across Europe and in North America, the costs associated with the preparation and planting of cuttings account for 60–70% of the total cost of willow stand establishment (Lowthe-Thomas et al., 2010). Sometimes the expense of

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planting materials alone account for more than 50% (Caslin et al., 2010). Increasingly, research has focused on improving the efficiency of planting willow crops, thereby also reducing the overall operational costs (Teodorescu et al., 2011; Lowthe-Thomas et al., 2010; Frenette-Dussault et al., 2019; Desrochers et al., 2020). It has been proposed that a key step for the application of phytoremediation using willow is a reduction of planting costs as well as an improvement of the viability and competitiveness of woody crops in the field (Larsen et al., 2014; Desrochers et al., 2020).

New trends in planting techniques of willow for environmental applications have been reviewed in this paper, including the type of planting materials, planting methods in the field, and as well as the main factors affecting the early establishment of willow crops. Different planting technologies for willow used in phytoremediation are proposed and provide a reference point for expanding the application of this phytotechnology for ecological land reclamation and restoration.

1. Planting materials

Vegetative propagation is very simple and convenient because of preformed root primordial on stem nodes. As a result, vegetative propagation by stems, shoot or branches has been long considered the cheapest and most flexible planting strategy for willow used in environmental applications (Rafay et al., 2015; Corseuil and Moreno, 2001). The size of planting materials, namely length and diameter, ranges from 1.5 to 300 cm and 2 to 40 mm, respectively. There are five types of planting materials for willow which are defined by their length and diameter, as shown in Table 1.

The planting materials currently used most widely are 1–2 m or 20–30 cm cuttings, which are inserted into the soil vertically (McCracken et al., 2010). In the horizontal planting, more suitable and shorter planting materials are also selected, mainly including billets 10 or 20 cm in length (Larsen et al., 2014; Edelfeldt et al., 2015), 2–5 cm long micro-cuttings (Guidi Nissim et al., 2016) and single-bud short branches 1.5–2.5 cm in length (Qin et al., 2018) (Table 1). Various planting materials with different specifications have been produced for use in complex, changing environments. Micro-cuttings and single-bud short shoots are smaller, making them easier to dehydrate. It has been suggested that micro-cuttings may be successfully established in the field by covering with organic matter and moisturizing (Frenette-Dussault et al., 2019; Desrochers et al., 2020). Single-bud short branches are only applied in cultivation under greenhouse conditions, which requires rooting liquid and foliar fertilizer to ensure germination and growth (Qin et al., 2018).

2. Planting methods

The survival and growth of stem cuttings, as well as the amount and distribution of roots, are critical for environmental applications of willow crops. Globally, there are eight types of planting techniques for willow in the field according to the size of planting materials and orientation. These techniques are listed in the Table 2: vertical cuttings, diagonal oblique insertion, lay-flat, billets and micro-cuttings, SALIMAT and DeValix. Each technique has its own planting method, supporting machinery and in some cases, preferable site characteristics (Fig. 1). In general, the techniques employing horizontal planting schemes are more abundant, making use of a wider variety planting materials and application scenarios.

Conventional willow establishment is performed using dormant hardwood cuttings planted vertically (Volk et al., 2016). The standard commercial method is to prepare 20-cm long hardwood cuttings which are then planted vertically in the soil (only 1–3 cm remains aboveground) using a Salix Maskiner Step-Planter or an Egedal Willow Planter (McCracken et al., 2010). Recently, Donnelly et al. (2019) demonstrated that 20-cm cuttings inserted diagonally into the soil, with half of the cutting remain aboveground, produced slightly higher stem yields than traditional vertically-planted cuttings in a field setting, although the opposite was true under greenhouse conditions (Donnelly et al., 2019). This technique is mainly suitable for abandoned farmlands with good texture soils where cuttings are easily inserted (Teodorescu et al., 2011). However, many sites with steep slopes, high compactness and stony land are unsuitable for mechanized planting operations (Frenette-Dussault et al., 2019).

Horizontal planting of willow cuttings has also been tested using various techniques. An alternative horizontal planting method is the lay-flat system, in which long willow (2–3 m) rods are placed in shallow trenches of various depths and covered with soil (McCracken et al., 2010). The lay-flat technique not only achieves yields equivalent to those of traditional vertical planting methods (McCracken et al., 2010; Larsen et al., 2014), but also reduces planting costs by 48% (Lowthe-Thomas et al., 2010). One disadvantage with the lay-flat technique is the amount of planting material used, which have been reported to be over three times as much plant material as required for conventional vertical planting (McCracken et al., 2010). The use of billets is another technique for willow propagation. It consists of 10 cm long cuttings harvested using a sugar cane harvester, dropped into the bottom of a shallow trench and covered with 2 cm thick layer of soil (McCracken et al., 2010). Field trials using billets generally save 17% of planting materials but reduce yields (5.6–8.6 $Mg \cdot ha^{-1} \cdot year^{-1}$ compared to 10.4 $Mg \cdot ha^{-1} \cdot year^{-1}$ using 1.8 m rods and 7.4 to 20.7 $Mg \cdot ha^{-1} \cdot year^{-1}$ using conventional 20 cm vertical cuttings (Labrecque and Teodorescu, 2003; McCracken et al., 2010; Larsen et al., 2014; Edelfeldt et al., 2015) (McCracken et al., 2010; Larsen et al., 2014; Edelfeldt et al., 2015). In addition, both lay-flat and billets, planted at a greater depth show a significant delay in emergence likely due to the increased time of the first produced shoots to reach the surface and start photosynthesis which gives weeds an advantage (Edelfeldt et al., 2015). In one trial, micro-cuttings 5-cm in length, prepared from non-dormant rods, were evenly spread on the soil surface and covered with a layer of organic matter for moisture retention (Guidi Nissim et al., 2016). This novel planting technique can reduce planting material costs by 16–60% (Guidi Nissim and Labrecque, 2016) and show promise in field applications due to significant inhibition of weed growth and competition, and a decline in labor costs for early management (Frenette-Dussault et al., 2019; Desrochers et al., 2020; Labrecque et al., 2020). This last example shows that it possible to both reduce the amount of planting material and labor costs depending on the chosen method.

The SALIMAT technique was developed in Belgium to establish willow vegetation on dredged sediment deposits, which horizontally place 2-m long willow rods wrapped and tied together around a central disposable tube using biodegradable string by crane and dragline (Vervaeke et al., 2001). The rods sink into the sediment under their own weight and are protected from desiccation by a water and silt layer (Vervaeke et al., 2001). It has exhibited successful establishment on dredged sediment and has potential for phytoremediation of contaminated soils (Vervaeke et al., 2001; Meers et al., 2005). However, this method is not suitable for use on sites with high sand or gravel content as well as the added limitation incurred by the cost and accessibility of a crane.

Table 1
Characteristics of planting materials of willow.

Planting material	Length (cm)	Diameter (mm)	Reference
Rods	50–300	20–40	McCracken et al., 2010; Manzone et al., 2017
Cuttings	20–30	10–25	Manzone et al., 2017
Billets	10	/	Larsen et al., 2014; Edelfeldt et al., 2015
Micro-cuttings	2–5	7.5–15	Guidi Nissim et al., 2016
Single-bud short shoots	1.5–2.5	2	Qin et al., 2018

Table 2
the methods and application condition of the planting technology of willow.

Planting technique	Specifications			Site characteristics	Reference
	Materials	Orientation	Machinery		
Vertical cuttings	Rods/cuttings	Vertical	Step planter / rotor planter	Good texture soil	Larsen et al., 2024
Diagonal oblique insertion	Cuttings	45°	None (performed manually)	Good texture soil	Donnelly et al., 2019
Layflat	Rods/cuttings	Horizontal	Layflat planter	All sites	McCracken et al., 2010; Bergante et al., 2016
Billet planting	Billets	Horizontal	sugarcane planter	All sites	Larsen et al., 2014
Microcutting planting	Micro-cuttings	Horizontal	None (performed manually)	All sites	Frenette-Dussault et al., 2019
SALIMAT	Rods	Horizontal	Crane and dragline	Sediment deposits	Vervaeke et al., 2001
DeValix	Rods	Horizontal	None (performed manually)	All sites	Vinhal et al., 2022

Fig. 1. The planting methods of vertical cuttings (a,b) and microcuttings (c,d) for willow plantation.

Recently, the DeValix technique was introduced as a novel method of willow establishment for environmental applications (Vinhal et al., 2022). It was designed and tested as an alternative horizontal planting method that not only can be implemented in a variety of environmental applications, but it is also easily moved and planted by hand. Six willow rods of 91.4-cm length are placed in a 'window' formation and tied together using biodegradable sisal twine to form a mat (Vinhal et al., 2022). Mats are placed on top of the substrate, covered with 5-cm of soil, and stabilized on sloped ground with 50.8-cm genotype-specific cuttings used as stakes (Vinhal et al., 2022). This technique appears to be a particularly promising establishment method for slope stabilization and phytoremediation applications where site conditions make vertical planting methods unsuitable. However, the main drawbacks of this method are that the current process of forming the mats by tying rods together manually with sisal twine is cost-prohibitive for commercial-scale installations as well as the difficulty in performing weed control.

There are also bioengineering approaches that have been developed to stabilize slopes or to colonize riparian zones. In a report he produced, Polster (2010) presents, in a well-illustrated manner, numerous ways to use willow stems to address this type of situation.

3. Factors influencing the early establishment of willow

Successful willow establishment is a significant determinant of the overall phytoremediation potential of willow plantations. The factors that play a decisive role include the overall quality of propagules (i.e., clones, cutting phenology, propagules size, pre-treatment measure) (Verwijst et al., 2012; Rafay et al., 2015; Edelfeldt et al., 2015), operation during planting (date (Teodorescu et al., 2011; Welc et al., 2017), orientation (McCracken et al., 2010; Edelfeldt et al., 2015; Dieterich and Martin, 2008) and planting depth (Dieterich and Martin, 2008; Cao et al., 2012; Edelfeldt et al., 2015; Han et al., 2017), post-planting management (i.e., ambient humidity and weed management (Sage., 1999; Larsen et al., 2014; Albertsson et al., 2014; Schulz et al., 2016; Welc et al., 2017). All these measures encompass the whole process of plant material preparation, installation and early maintenance management for willow vegetation.

3.1. Cutting characteristics

The species and variety selection of willow is very important for the early establishment and growth of sprouts. The flushing time, the number of sprouts and biomass production (Zamora et al., 2014; Han et al., 2017; Welc et al., 2018) are genotype-dependent factors. For instance, it was observed that when using cuttings of the same length, *S. viminalis* began to sprout after 4 days, whereas *S. eriocephala, S. amygdaloides* and *S. dasyclados* sprouted later, with a maximum difference of 2 weeks (Sennerby-Forsse and Zsuffa, 1995; Welc et al., 2018). The flushing time of the first-generation hybrid (*S. schwerinii* × *S. viminalis*) was also shorter than that of the second-generation hybrid (Welc et al., 2018). A short flushing time, along with long duration of leaves and photosynthesis, is related to the growth of branches and biomass production (Vigl and Rewald, 2014). Thus, the species and varieties with early flushing would be preferred for most sites and projects.

The position on the branch from which cuttings are made from can have a profound impact on the sprouting efficiency and the early establishment of cuttings (Teodorescu et al., 2011; Verwijst et al., 2012; Guidi et al., 2013; Welc et al., 2018). It is well established that cuttings obtained from the tip of the branch provide earlier sprouting, with a greater number of newly-formed shoots and higher biomass yield than those obtained from the base of the stem (McCracken et al., 2010). Moreover, buds on the tips of the cuttings progress earlier with regard to phenology than those from the basal parts. When fragmented, apical dominance is still present in each cutting, with the part of the cutting closest to the tip of the original branch acting as a new tip and producing the highest number of shoots (Edelfeldt et al., 2015). The apical dominance could be especially important in lay-flat planting, leading to fewer sprout emergence when basal portions of the cuttings are used which in turn benefits weeds. On the other hand, although the use of non-dormant cuttings may reduce some operation costs (e.g., storage cost for cuttings), the establishment of the material is less reliable due to lower reserves of carbohydrates and nutrients when it harvested and planted later in the season in comparison to dormant cuttings (Welc et al., 2017, 2018). Thus, it is widely recommended that non-dormant cuttings be planted as soon as harvested, that means within hours following their harvest, especially to prevent them from drying out. Cutting size in general (both length and diameter) is an important factor that determines the rooting and growth of sprouts which should be chosen according to soil properties and planting technique. (Vigl and Rewald, 2014; Manzone et al., 2017)). In general, cutting lengths of 15–25 cm (Edelfeldt et al., 2015) and a minimum diameter no less than 8–9 mm (Dawson et al., 2007) has been frequently recommended for commercial planting material. Within a certain length range (10–50 cm), the propagules are longer, increasing the values of growth parameters such as the survival rate of plants, the number and height of sprouts, and the biomass yield (Rossi, 1999). It also has been proposal that cuttings should not be less than 14 cm long (Edelfeldt et al., 2015) and the minimum diameter should not be less than 8–9 mm (Dawson et al., 2007). Together with the considerable cost of cutting material in the establishment of a new plantation, cuttings of about 20 cm in length are most commonly recommended in most European and Northern American countries (Abrahamson et al., 2002; Snowdon et al., 2008). In general, it is reported that athere is a strong linear relationship between the diameter of cuttings and the biomass of new roots. In the same manner, several authors have found that willow generally increases with cutting length and diameter (Vigl and Rewald, 2014; Sun et al., 2014; Heinsoo and Tali, 2018). However and on the contrary Burgess et al. (1990) found that cuttings longer than 22.9 cm did not result in any significant increase in growth in *Salix alba*. The positive effects of cutting size are generally attributed to the amount of non-structural carbohydrate and nitrogen reserves available for allocation to roots and shoots in the early establishment phase (Gage and Cooper, 2004; Brereton et al., 2014). When taking single bud short branches (2 mm diameter, 1.5–2.5 cm long) as propagules, rooting solution and foliar fertilizer are added to provide external nutrition (Qin et al., 2018). In addition, the cutting length may also be associated with the ability to withstand dryer soils, with longer cuttings exhibiting greater tolerance to soil desiccation (Gage and Cooper, 2004).

Pre-planting treatments play a key role in improving the success of stem cuttings to develop roots and shoots, as well as overall plant survival (Volk et al., 2004). Common pretreatments can be divided into two types, namely cold storage and pre-soaking (McCracken et al., 2010; Edelfeldt et al., 2018). In conventional practice, planting materials are harvested during winter and kept in cold storage at a constant temperature (0–4 °C) until planting (Teodorescu et al., 2011; Guidi et al., 2013). Cold storage is logistically demanding and encompasses approximately 3–5% of the entire cost of planting material (Welc et al., 2018). Studies have pointed to risks of desiccation and show that a prolonged time (2 weeks) of field storage after cold storage may lead to a decrease in survival, growth rate and biomass production (Volk et al., 2004; Verwijst et al., 2012). In recent years, different studies have proven that the aboveground biomass and competitiveness of non-dormant cuttings in early spring are comparable to those of dormant cuttings. Non-dormant branches in early spring can be directly planted in the field as propagules, indicating that cold storage of cuttings was redundant when willow was planted early in the growing season (McCracken et al., 2010).

Pre-soaking of willow stems prior to planting is currently practiced by commercial operators in Ireland and may have stemmed from a practical approach to avoid desiccation before planting (Donnelly et al., 2019). This technique not only increases the weight, length and number of root primordia (Edwards and Kissock, 1976) but also improves the survival rate of cuttings and plant biomass (Schaff et al., 2002; Pezeshki et al., 2005; Tilley and Hoag, 2009). Tilley and Hoag (2009) found in a riparian restoration project that pre-soaking willow for 14 days before spring planting on river banks improved establishment. Additionally, Schaff et al. (2002) found that 10 days of pre-soaking prior to planting improved growth, biomass and survival rate in black willow used for riverbank restoration projects. Pre-soaking is not only a common, simple, and inexpensive way to enhance shoot and root initiation, it is also a reliable practical method to avoid desiccation, thereby improving the overall survival rate of willow crops (Schaff et al., 2002; Donnelly, 2019). Therefore, the quality of propagules and early cutting establishment can be improved by soaking the propagules prepared from non-dormant branches in early spring. However, the pre-soaking period should not exceed 10 days, as roots may start to develop on the cuttings, making their planting difficult and affecting their survival.

More rarely, the use of rooting hormone (IBA, indole-3-butyric acid) has been employed to promote better rooting (Ficko and Naeth, 2022). However, we believe that this practice could be more expensive and complicated to implement operationally.

3.2. Planting date

Studies on the planting time of willow have paid more attention to the efficiency of mechanical operations (Manzone et al., 2017; Manzone and Balsari, 2015), whereas only a few studies have focused on the effects of different planting times or duration (Teodorescu et al., 2011; Welc et al., 2017). This may be related to the long-term use of dormant cuttings (Kuzovkina and Quigley, 2005; Tognetti et al., 2013; Larsen et al., 2014). After harvest in winter, dormant branches are refrigerated at −4 °C, and the stored resources such as non-structural carbohydrates and nitrogen are effectively preserved, making the future development of new roots and shoots less affected by the planting date. In the high latitudes of the northern hemisphere (such as Sweden, Canada and United States), the planting time lasts from early May to mid-June (Guidi et al., 2013; Welc et al., 2017). In an experiment aimed at testing the impact of different planting dates over a one-month period in spring, Teodorescu et al. (2011) fond that the highest performance was achieved with *Salix viminalis* ('5027'), which can be planted up to a month later without demonstrating any notable decrease in biomass production or on survival rate. However, biomass production from dormant cuttings of three willow cultivars was approximately 55–89%

higher when planted in early May as compared with early July. Welc et al. (2017) found that due to the migration of carbohydrates and growth hormones in non-dormant branches, the later the harvest and planting, the more rapidly the resources stored in the cuttings are consumed, thereby increasing the accumulated temperature days required for bud germination. Furthermore, with changes in light (both duration and intensity) conditions and temperature in spring, the alternations in carbohydrate reserves and hormone pathways involved in the bud germination process become increasingly more sensitive.

3.3. Orientation of planted material

Studies comparing horizontal planting with traditional vertical planting have not shown consistent results (Edelfeldt et al., 2015). Lowthe-Thomas et al. (2010) found that stem diameter, weight and estimated yield were significantly larger for the lay-flat system after three growing seasons. Gro and Culshaw (2001) found that the lay-flat system produced more biomass during the first year and had greater canopy density than traditional planting, while billets, susceptible to dehydrate, exhibited shortcomings with some of the planted areas failing. The diagonally planted stems produces nearly 15% more biomass and achieved significant increases in stem numbers in the field trials relative to vertically planted stems (Donnelly et al., 2019). While McCracken et al. (2010) found that yield per unit area from billets was lower after two 3-year consecutive harvest cycles, but no significant difference in yield between lay-flat rods or vertical cuttings was observed. Edelfeldt (2015) found that vertically planted cuttings produced more biomass and shoots per length unit than horizontally planted cuttings. Field studied conducted in eastern Canada, also reported that biomass production from willow micro-cuttings lead to similar biomass production to that of traditional vertical planting (Frenette-Dussault et al., 2019).

In the specific process of implementation, horizontal planting also has quite a few advantages. Firstly, horizontal planting with 1–2 m rods could reduce the time and cost of cutting preparation (Manzone et al., 2009). Secondly, the lay-flat planter is able to plant at a faster rate than the step planter and is able to use a wider range of planting material, reducing the overall cost of planting cost (Lowthe-Thomas et al., 2010). Therefore, horizontal planting is considered to be a valuable alternative to traditional planting techniques, but it needs to be guaranteed by selecting the appropriate length and planting depth. We know that some willow producers in Canada are increasingly using this approach, but it has not been scientifically monitored and documented.

3.4. Planting depth

Several studies have shown that the planting depth of cuttings may affect the growth of willow for both vertical and horizontal planting techniques (Edelfeldt et al., 2015; Han et al., 2017). In most cultivation manuals, recommendations are that only 1–3 cm of a 20-cm long cutting remains aboveground, which is recognized as deep planting (Snowdon et al., 2008). Such deep planting is supposed to provide the cutting with good soil contact, minimize the risk of drying out and improve biomass yield using rich soil moisture and nutrients (Weih, 2009; Sun et al., 2014). In contrast, shallow planting with a longer portion of the cutting protruding above ground level (e.g., 10 of a 20-cm long cutting) has the potential to result in the production of a greater number of shoots since number of shoots per cutting increases with cutting length (Rossi, 1999; Verwijst et al., 2012; Donnelly et al., 2019). Some studies have shown that deep planting may increase the aboveground biomass yield by about 40% in comparison with shallow planting, while no significant different was found in root biomass (Han et al., 2017). The enhanced yield results from the reliable soil water supply in the deeper soil layer that the roots were able to exploit.

In horizontal planting schemes cuttings should not be planted deeper than 5 cm since it has been observed that at depths greater than this limit, the survival rate and overall plant productivity is negatively affected (Edelfeldt et al., 2015). In fact, although some shoots produced below the soil line may finally reach the surface, the extended time required for the photosynthetic machinery to begin working will result in less shoot growth (Dieterich and Martin, 2008; Edelfeldt et al., 2015). Thus, excessively late shoot emergence delays development above ground, allow weeds to compete more with willows and reduces the length of the growing season available to the plant.

3.5. Soil conditions

Stable soil moisture and adequate nutrient supply are important determinants of willow plant biomass (Han et al., 2017), since the water and nutrient availability is one of the main factors affecting root development and growth (Sennerby-Forsse and Zsuffa, 1995). Positive effects of soil on growth and survival are attributed to water holding capacity and nutrient supply which is the important characteristics of soil with good agronomic traits (fertile loam texture) (Souch et al., 2004; Edelfeldt et al., 2013). Moreover, soils with a higher stony composition may negatively affect shoot emergence, thereby affecting shoot growth. Some negative effects have been observed during the first year, when the root system is shallow and the roots are young and more susceptible to compaction damage (Souch et al., 2004). Planting in compact soils, not only limits subsequent root growth and development by may also cause direct damage to cuttings when they are pushed into the soil by the planting machine (Edelfeldt et al., 2013).

Compared with unimproved sites, the establishment and planting efficiency of willow with organic fertilizer also promoted plant growth and biomass production (Cavanagh et al., 2011; Dimitriou et al., 2011). The addition of organic mulch can improve soil moisture content and thus protect cuttings from desiccation (Desrochers et al., 2020). In a greenhouse environment, the germination rate of micro-cuttings reached 100% through the application of organic mulch (Guidi Nissim and Labrecque, 2016). Even under field planting conditions, willow micro-cuttings covered with agricultural organic mulch have germination rates of about 46%, and ensure that biomass yield is comparable to that of cutting planting (Frenette-Dussault et al., 2019).

3.6. Weed control

A very important part of the establishment process is appropriate weed management during the first and second year, during which the willow plants have low competitive ability with weeds (Larsen et al., 2014; Welc et al., 2018). Plant mortality has been found to be ranging from 2.7% to 37.4% with shoot biomass yield reduction between 46 and 96% for willow without weed control compared to willow with weed control (Albertsson et al., 2014; Sage., 1999). Annual weeds mainly affect the first year's growth until the willow crop has grown competitive, while perennial weeds may seriously hamper the crop over the course of its lifetime (Sage., 1999; Larsen et al., 2014). Moreover, the early plant size variation caused by weed competition will also expand over time, resulting in plant size differentiation and stand gaps (Verwijst, 1996). Therefore, appropriate weed management is essential in the first year of willow cutting establishment, especially before the sprouts have attained certain competitiveness.

Chemical and/or mechanical weed control is strongly recommended when establishing a willow plantation. Weeds can be controlled by various herbicides although some herbicides may also cause damage on the willow crop (Bergkvist and Ledin, 1997). Alternatively, weed control may be done by mechanical methods or by using combination of mechanical and chemical weed control methods; however, mechanical methods are not especially effective in perennial weeds control (Schulz et al., 2016). Mulch could also be considered for weed management, especially if invasive species or weeds are potential competitors with willows (Bartley et al., 2015). Labrecque et al. (1994) have shown that the use of plastic mulch can be very effective in controlling weeds while promoting faster plant establishment. However, this practice is not feasible on a large scale. Additionally, ground cover could inhibit or delay the emergence of weed, which allows willow to be more competitive as soon as them reach a height of the more than 50–60 cm because they create enough shade to suppress competing plants.

4. New trends

Willow is an ideal plant material for phytoremediation. However, the way to improve the establishment efficiency and reduce costs in environmental applications has become a nodal point for its large-scale implementation. Based on an extensive literature review, the following conclusions can be drawn: (1) The use of non-dormant willow material (including rods, cuttings, billets, micro-cuttings and single-bud short shoots) collected and planted in early in the spring instead of dormant material which relies on expensive cold storage can achieve fast establishment, higher growth rate and biomass yield. (2) New planting approaches have been recently proposed showing promising economical and effectiveness characteristics. These include lay-flat planting, billets and micro-cuttings which can provide equivalent or higher biomass yield than conventional planting methods. These approaches can reduce the amount of planting materials, time and manpower (3) For environmental applications of willows, vertical planting should be performed by leaving a short portion (1–3 cm) aboveground, while horizontal approaches should not bury the plant material more than 5 cm in the soil. (4) To achieve the early establishment of willow, soil moisture should be always assured and weed control should be performed regularly over the first two years. An effective weed control measures involved the ground cover for regulation of relative emergence time and mechanical removal should be implemented in field. Thus, by integrating the advantages of non-dormant branches, small-sized cuttings, horizontal orientation planting, and ground cover using mulch, a series of innovative willow planting technologies such as micro-cuttings and billets, have been developed for environmental applications in field. These technologies are designed to address unfavorable conditions, including harsh and contaminated soil that is unsuitable for traditional machinery and the risk of human exposure pollution.

CRediT authorship contribution statement

Kankan Shang: Conceptualization, Data curation, Funding acquisition, Resources, Writing – original draft. **Michel Labrecque:** Conceptualization, Data curation, Formal analysis, Supervision, Writing – original draft, Writing – review & editing. **Vincent Gilles:** Conceptualization, Data curation, Funding acquisition, Resources, Supervision. **Werther Guidi Nissim:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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