Solid Earth

Relationship between hydraulic properties and plant coverage of the closed-landfill soils in Piacenza (Po Valley, Italy)

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Abstract. In this paper the results of a study of soil hydraulic properties and plant coverage of a landfill located in Piacenza (Po Valley, Italy) are presented, together with the attempt to relate the hydraulic properties in relation with plant coverage. The measured soil water retention curve was first compared with the output of pedotransfer functions taken from the literature and then compared with the output of the same pedotransfer functions applied to a reference soil. The landfill plant coverage was also studied. The relationship between soil hydraulic properties and plant coverage showed that the landfill soils have a low water content available for plants. The soils' low water content, together with a lack of depth and a compacted structure, justifies the presence of a nitrophilous, disturbed-soil vegetation type, dominated by ephemeral annual species (therophytes).

1 Introduction

Soil water is a fundamental resource for the components of the ecosystem; it plays a vital role in determining the functioning of plants and other soil biota (Brevik et al., 2015). Soil physics is largely related to the interaction between soil and water; therefore the physical, chemical and biological processes that take place in soil depend on the amount and composition of water (Brevik et al., 2015). With this in mind, knowledge of the hydraulic properties of soils is important in many scientific disciplines, from agriculture to ecology, since the amount of water, and the strength by which it is held by soil, represents the characteristics of soil behaviour and for the vegetation and all other organisms' development.

Land use can significantly affect soil properties, such as bulk density, saturated hydraulic conductivity, infiltration rate and available soil water content (Haghighi et al., 2010), and it has been shown to be one of the main factors controlling soil water variability (Qui et al., 2001; Pan and Wang, 2009). Because soil properties are the main factor controlling soil water variation (Vachaud et al., 1985, Famiglietti et al, 1998; Hu et al., 2010), land use could influence soil water variations by changing soil properties (Gao et al, 2014). In recent studies, the effects of land use on soil water variation have been investigated via statistical analysis (Fu et al., 2003; Chen et al., 2007; Gross et al., 2008), simulation, or physical-based models (Li et al., 2009). Gao et al. (2014) demonstrate, through a study in a small catchment of the Chinese Loess Plateau, that land use can lead to spatial variation of soil water but has a negligible effect on soil water temporal patterns.

Soil moisture influences soil behaviour; it takes an important role, for example, in soil erosion. Antecedent soil moisture content, together with rainfall intensity, slope steepness and land use/land cover are factors influencing soil erosion and runoff (Ziadat and Taimeh, 2013). The effect of antecedent soil water content on soil erosion is still a matter of debate, as an opposing effect has been reported on aggre-

gate breakdown and seal formation (Vermang et al., 2009). Wet soils double the runoff coefficient and shorten the time to runoff, compared with the same soil when dry (Li et al., 2011). Greater soil erosion was observed during the wet season in Spain (Cerdà, 2002; Ziadat and Taimeh, 2013).

Soil water/moisture is also a key factor affecting vegetation structure in a water-limited environment (Rodriguez-Iturbe et al., 1999); in turn, vegetation exerts vital control on the entire water balance (Rodriguez-Iturbe et al., 2001) via complex and mutually interacting hydrological processes (Porporato et a., 2002; Gao et al. 2014).

In this paper, the study of hydraulic properties of soil is presented, by laboratory analysis, by using predictive models and by studying soil vegetation cover.

Direct measurements of soil hydraulic properties are rarely performed because they require lengthy and costly analysis; as an alternative, analysis of existing databases of measured soil hydraulic data may result in pedotransfer functions (PTFs) (Wösten et al., 2001). These functions often prove to be good predictors for missing soil hydraulic data. The PTFs show empirical relationships between soil hydraulic properties and some more easily measurable basic soil properties such as texture, bulk density and organic carbon content (Baker, 2008; Bouma and van Lanen, 1986; Pachepsky and Rawls, 2004; Vereecken et al., 2010; Wösten et al., 2001). To derive the PTFs, databases of soils from all over the world were used. Generally soil databases emphasize soil taxonomy and provide limited unsaturated soil hydraulic data. With this in mind, the international Unsaturated Soil Database (UNSODA) (Leij et al., 1996) and subsequently, the European database of soil hydraulic properties (HYPRES) (Nemes et al., 2001a; Wösten et al., 1999; Wösten and Lilly, 2004) were developed. Both these databases contain a wealth of information about soil hydraulic data, measurement methods and other relevant soil data (Nemes et al., 2001a).

The processing of the PTFs can be performed using computer programs such as CalcPTF 3.0 (Guber and Pachepsky, 2010), ROSETTA (Schaap M.G., et al., 2001) (which is available as stand-alone program and also as a part of the simulation model HYDRUS 1D; Simunek, et al., 2008), SOILPAR (Acutis and Donatelli, 2002) and SPAW (Saxton and Willey, 2006).

The relationship between volumetric water content and matric potential is shown by the soil water retention curve, which allows the derivation of available water for plants by comparing the water content at different applied suction (negative pressure) values.

In recent decades the increase in human population and human activity has resulted in an ongoing depletion of soil resources, to the point that the authorities have included the recovery of degraded areas in their priorities. The lower ability to make water available for plants and microorganisms is characteristic of a degraded soil; thus, in order to carry out

soil restoration, it is important to know its hydraulic properties.

In this work a degraded cover soil of a landfill located in Piacenza was studied. The soil used to closed the landfill is a natural soil, which comes from different areas near Piacenza, and it can be classified as an Anthrosol (FAO World Reference Base for Soil Resources): a soil formed or profoundly modified through long-term human activity, such as from addition of organic waste or household waste, irrigation or cultivation. This soil has shown very low fertility for more than 30 years; there is no chemical contamination justifying its condition, so the soil can be described as a degraded soil.

Recently the landfill soils and the vegetation were studied, and so the site environmental quality is described, including the relationship between soil chemical analysis and ecological indicators (Manfredi et al., 2012), the floristic–vegetational indexes (Giupponi et al., 2013b) and the presence and development of Onopordum acanthium subsp. acanthium (Giupponi et al., 2013a). The area is actually involved in a Life + project (Life 10 ENV/IT/000400 New Life, http://www.lifeplusecosistemi.eu), which includes among its objectives the treatment of degraded soils through an innovative reconstitution method to improve their quality, and the restoration of the closed landfill.

Restoration of closed landfills is essential to minimize the adverse effect on the environment and to render the landfills safe for further use (Chen et al., 2015). A lot of studies on landfills can be found in the literature – about root contamination by gas (Gilman et al., 1982), methane production (Themelis and Ulloa, 2007), microbiological studies (Boeckx et al., 1996) and ecological performance after the restoration of plant and animal communities (Chen et al., 2015; Wong et al., 2015) – but nothing can be found about hydrological properties of cover soil in relation to plant coverage.

The study of the vegetation cover of an area can be very useful as a tool to compare and corroborate the results of chemical and physical analysis performed on soil. The integrated study of different scientific disciplines in the description of an area is always preferred in order to have as complete an overview as possible. The study of the relationship between soil hydraulic properties and plant coverage, and the use of plant communities to assess the soil quality is a very interesting research field. This new way of studying an area can be applicable not only in describing degraded areas, but also when applied in other research fields, such as rural areas, road embankments, mining, badlands or border areas.

Novara et al. (2011) demonstrate that an appropriate choice of cover crops assists in very effective soil management in vineyards in Sicily. A natural reforestation following a different land use on the flood plain in the Dragonja sedimentation basins has resulted in a change in sedimentation rate (Keesstra, 2007; Keesstra et al., 2009). A study performed in a restoration program in South East New Territories landfill in Hong Kong, between pioneer species and

native species – including the investigation of different planting techniques, the use of different types of soil ameliorants and a focus on understanding what factors are most important in the growth of plants – provided valuable information for restoring subtropical engineering landfills (Wong et al., 2015). The vegetation, climate and environmental change have been used to explain the reasons of the severe soil erosion in the Loess Plateau of China (Zhao et al., 2013). Zornoza et al. (2015) use vegetation cover for the development of an index to assess the state of human disturbances in alpine grassland with different levels of degradation based on plant cover, production, proportion of primary plant and height of the plant. Studies of the vegetation biodiversity, together with chemical and physical soil analyses and the testing of the presence/abundance of soil microbes and soil fauna, are also used to assess the soil quality in some farms in Iceland and Austria (van Leeuwen et al., 2015).

Considering the importance of soil moisture and vegetation cover, the aim of this work is to relate the hydraulic properties of landfill soil with its vegetation, and to assess whether predictive systems (PTFs) are suitable for predicting these data.

2 Materials and methods

2.1 Study area

The closed landfill of municipal solid waste of Borgotrebbia is located in the territory of Piacenza (Po Valley, Italy, coordinates: 45°03′58″ N, 09°39′06″ E) at an altitude of 60 m. It has an area of 200 000 m^2 and is located along the right bank of the Trebbia River near its confluence with the Po River. Climatic data show that the average annual temperature is 13.3° C, while the average annual rainfall amounts to 778 mm, most of which is concentrated in the periods of March and September.

The landfill was opened from 1972 to 1985 and then was closed and covered with a layer, about 50 cm in depth, of different degraded soils left to be spontaneously colonized by plants. The soils used to close the landfill are loamy soils with a predominantly multi-faceted structure; they have low porosity and, by their nature, they are compact. Further compaction of the soil was induced by compression, caused by operations carried out in order to close the landfill so that the leakage of gas and infiltration by rain could be avoided.

2.2 Soil

2.3 Physical-chemical analysis of the soil

Eleven sampling points were chosen as being representative of the closed landfill area after a preliminary study. Initially they were sampled in the area at 51 points, following a grid division NE–SW, NW–SE; and the distribution of the observed different vegetation types – the plant communities differ in structure and floristic composition according to the different environmental factors such the type of soil. By statistical elaboration of the 51 chemical analyses, 11 soils resulted in being the most representative of the area.

The 11 soil samples were taken at 25 cm depth and chemical and physical analyses were carried out based on the Methods of Soil Chemical and Physical Analysis as described in the Official Gazette of the Italian Republic: texture and grain size (Italian position Method II.5 Suppl. Ord. G.U. no. 248/21.10.1999; international position ISO 11277), primary and secondary structure, organic carbon (Italian position Method VII.3, Suppl. Ord. G.U. no. 248/21.10.1999, Walkley-Black,), salinity (Italian position Method IV.1 Suppl. Ord. G.U. no. 248/21.10.1999, international position ISO 11265, aqueous extract 5 : 1), total limestone (Italian position Method V.1, Suppl. Ord. G.U. no. 248/21.10.1999, international position ISO 10693) and water potential (Italian position Method VIII.3, Suppl. Ord. G.U. no. 173/02.09.1997, international position ISO/DIS 11274, sand box and Richards plates; measurements performed on undisturbed samples). The results of the physical–chemical analyses were used as input for the elaboration of 18 different PTFs (Tables 1 and 2). As the bulk and particle density of samples aren't measured, the literature values for loamy soils were used: bulk density 1.3 g cm^{-3} and particle density 2.3 g cm^{-3}.

2.3.1 Water retention models

Most mathematical models that describe soil hydrologic behaviour are based on non-linear relationships between the volumetric water content in the soil, θ, the suction applied by the soil, h, and the hydraulic conductivity (Hillel, 1998); the functions $\theta(h)$ and $K(h)$ describe the hydraulic properties of a soil through a parametric equation (Leij et al., 1997). Some predictive methods for estimating hydraulic conductivity are based on direct observations of water content in the soil measured at different values of suction (Romano and Palladino, 2002). To compensate for all the cases in which it is not possible to measure it, a group of functions called pedotransfer functions (PTFs) has been developed. PTFs correlate the water retention and hydraulic conductivity with some easily measurable chemical and physical properties of the soil such as texture, density, porosity, and organic carbon content (Elsenbeer, 2001; Tietje and Hennings, 1996; Tapkenhinrichs and Tietje, 1993). Most PTFs are regression equations that are derived from data collected during specific campaigns and are reliable for describing the soil hydraulic properties (Romano and Palladino, 2002).

In this work, the measured water retention curves were compared with those obtained using 17 PTFs proposed in the literature that are based on databases of soils distributed worldwide following two models: Brooks and Corey (1964) and van Genuchten (1980), (Rawls et al., 1998, 1992, 1982a; Saxton and Rawls, 2006; Saxton et al., 1986; Tanij, 1990).

Table 1. Results of chemical and physical analyses performed on soils. Legend: A.B.: angular blocky; Sa.B.: subangular blocky; G.: granular; P.: platy; S.G.: single grain.

Sample	Organic carbon content %	CaCO₃ g kg⁻¹	Electrical conductivity ds m⁻¹	Sand %	Silt %	Clay %	Soil thickness cm	Structure of soil
1	1.94	130.2	0.197	21.9	12.3	65.8	55	A.B.–Sa.B.
2	4.13	147.7	0.212	17.5	12.9	69.6	30	G.–Sa.B.
3	4.14	190.4	0.152	27.9	12.3	59.8	60	G.–Sa.B.
4	1.67	38.5	0.232	11.5	14.7	73.8	30	Sa.B.–G.
5	1.04	134.8	0.167	12.2	12.4	75.4	62	P.
6	1.35	57.4	0.196	10.3	14.7	75	32	Sa.B.–G.
7	1.92	229.8	0.130	33.3	12.5	54.2	45	S.G.–Sa.B.
8	4.10	266.7	0.288	16.7	16.8	66.5	47	A.B.–G.
9	2.35	138.1	0.252	25	12.3	62.7	47	A.B.–Sa.B.
10	2.68	59.9	0.136	18	9.8	72.2	50	Sa.B.–A.B.
11	3.63	128.9	0.248	17.8	12.3	69.9	40	Sa.B.–G.

Table 2. Volumetric water content (θ %) from instrumental analysis at different suction values.

Sample	Suction (−kPa)							
	0.10	0.25	1	3	6	10	33	1500
1	49.45	43.58	39.21	37.23	35.88	34.54	27.60	24.66
2	48.75	44.27	41.05	38.62	37.61	36.98	28.46	27.91
3	47.77	45.12	41.83	37.00	34.80	33.83	25.71	13.57
4	49.42	45.87	40.40	35.46	32.77	31.13	22.91	22.32
5	44.09	41.77	37.31	33.07	31.20	30.01	21.73	18.92
6	47.46	45.06	41.60	38.08	36.02	34.85	25.29	14.59
7	44.55	40.98	38.32	33.25	30.97	29.48	19.37	10.86
8	45.63	45.15	44.21	43.46	42.71	42.30	37.02	26.50
9	51.01	47.71	42.76	37.37	33.58	30.55	23.27	20.84
10	54.43	52.41	47.81	41.39	38.38	35.18	26.08	14.02
11	52.16	43.94	39.52	37.90	37.27	36.78	29.09	25.69

The functions used to describe water retention properties are the following: the van Genuchten (1980) water retention equation, as in

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left[1 + (\alpha h)^n\right]^m} \qquad (1)$$

and the Brooks and Corey (1964) equation:

$$\frac{\theta - \theta_r}{\phi - \theta_r} = \begin{cases} \left(\frac{h}{h_b}\right)^\lambda, & h > h_b \\ 1, & h \leq h_b, \end{cases} \qquad (2)$$

where θ is the volumetric soil water content (cm³ cm⁻³); θ_r is the residual soil water content (cm³ cm⁻³); θ_s is the saturated soil water content, (cm³ cm⁻³); ϕ is the soil porosity, (cm³ cm⁻³); λ is the pore size distribution index (dimensionless); h is the capillary pressure (cm); h_b is the air-entry pressure (cm); α is the parameter of the van Genuchten equation, corresponding approximately to the inverse of the air-entry

value, (cm⁻¹); m, n are the empirical shape-defining parameters in the van Genuchten equation, (dimensionless).

The values of the parameters (θ, θ_r, θ_s, ϕ, λ, h_b, α, m, n) are predicted by PTFs, which are developed from the measured data set (Wösten et al., 2001).

In this study the processing of the PTFs was performed using the program CalcPTF 3.0 (Guber and Pachepsky, 2010). This contains a class of PTFs generated from the HYPRES database; see Table 3.

CalcPTF 3.0 is a computer program developed to calculate PTFs in order to estimate parameters of the Brooks and Corey model and the van Genuchten model. The inputs used in this program are: soil texture, organic carbon content, bulk density and particle density.

The database HYPRES (Hydraulic Properties of European Solis; Wösten et al., 1999) draws together some basic soil information and soil hydraulic data from which PTFs applicable to Europe can be derived (Nemes et

Table 3. Authors and localization of database and model used for the different PTFs. Legend: VG represents van Genuchten, BC represents Brooks–Corey.

PTF	Region	Model
HYPRES	Europe	VG
Saxton et al. (1986)	USA, nationwide	BC
Campbell and Shiosawa (1992)	None particular	BC
Rawls and Brakensiek (1985)	USA, nationwide	BC
Williams et al. (1992)	Australia	BC
Williams et al. (1992)	Australia	BC
Oosterveld and Chang (1980)	Canada, Alberta	BC
Mayr and Jarvice (1999)	UK	BC
Wösten et al. (1999)	Europe	VG
Varallyay et al. (1982)	Hungary	VG
Vereecken et al. (1989)	Belgium	VG
Wösten et al. (1999)	Europe	VG
Tomasella and Hodnett (1998)	Brazil	VG
Rawls et al. (1982b) (corrected for OM according to Nemes et al., 2009)	USA, nationwide	VG
Gupta and Larson (1979)	Central USA	VG
Rajkai and Varallyay (1992)	Hungary	VG
Rawls et al. (1983) (corrected for OM according to Nemes et al., 2009)	USA, nationwide	VG

al., 2001b). Using the HYPRES database, two different sets of PTFs were derived: class pedotransfer functions and continuous pedotransfer functions. Class PTFs predict the hydraulic characteristics for each of the five texture classes (coarse: clay < 18 % and sand > 65 %, 18 % < clay < 35 % and 15 % < sand; medium: clay < 18 % and 15 % < sand < 65 %; medium fine: clay < 35 % and sand < 15 %; fine: 35 % < clay < 60 %; very fine: 60 % < clay) and for two pedological classes within them (topsoils and subsoils) plus an additional class which encompassed the organic soil horizons. Continuous pedotransfer functions can predict hydraulic properties from individual measurements of soil texture, organic carbon content and bulk density.

The goodness of the PTFs and their ability to describe the hydraulic characteristics of the landfill coverage soils was calculated through the root mean square error (RMSE) test based on the difference between the values of volumetric content of water at different suction values, measured and estimated, starting from the following equation:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(\theta_i - \theta_i^*\right)^2}, \tag{3}$$

where N is the number of measurements; θi and $\theta i*$ is the volumetric water content (θ %), measured and estimated.

The hydraulic data of the landfill cover soils obtained instrumentally and through PTFs were also compared with those of a reference soil. The reference soil chemical-

physical properties are chosen to describe a non-degraded natural soil with the same texture, i.e. silt loam, with a bulk and particle density of respectively 1.3 and 2.3 g cm^{-3} of landfill soils but with an average organic carbon content of 1 %, which is typical of Piacenza natural soils, well structured and with a depth of 1 m. The volumetric water content of the reference soil at different suction values was calculated through the arithmetic mean of the water contents from the 17 PTFs, so it is possible to achieve an estimate of available water content.

2.4 Flora and vegetation

The vegetation data were collected by making up 52 phytosociological relevés using the Zurich–Montpellier school method (Braun-Blanquet, 1964). The sampling sites were selected to summarize the vegetation of the whole area. Each relevé included an area of 16 m^2 (4 m × 4 m) and was geo-referenced. For each sampling site, the plant species present were listed and their cover was estimated using the values of the Braun–Blanquet conventional scale (r = sporadic species; + = < 1 %, 1 = 1–5 %, 2 = 5–25 %, 3 = 25–50 %, 4 = 50–75 %, 5 = 75–100 %). The relevés were periodically monitored from April to September 2012.

Pignatti (1982) was consulted for the identification of the species, while the specific nomenclature is according to Conti et al. (2005). In order to process the biological spectrum of the plant list, the data concerning the biological form according to Raunkiaer (1934) (therophytes – T: annual herbs; hemicryptophytes – H: perennial herbs; geophytes – G: perennial herbs with underground storage organs; chamaephytes – Ch: woody plants with buds at no more than 25 cm above the soil surface; phanerophytes – P: trees and shrubs with buds over 25 cm above the soil surface) were taken from Romani and Alessandrini (2001).

Landolt's F index (soil moisture) (Landolt, 1977), updated by Landolt et al. (2010), provides a guide on the need of water by plant species during their growth period. The F values range from 1 to 5 (1 is very dry, 1.5 is dry, 2 is moderately dry, 2.5 is fresh, 3 is moderately moist, 3.5 is moist, 4 is very moist, 4.5 is wet and 5 is flooded or submerged) and were attributed to all the species, recorded in order, to obtain information on the degree of humidity of the landfill soil cover. To each species was also assigned its respective life strategy according to Grime (2001, 1979) (c describes competitive strategists, r describes ruderal strategists and s describes stress-tolerant strategists); this information was retrieved from Landolt et al. (2010), according to the adjustments proposed by the author. Starting from the climate, soil and vegetation data, reference crop evapotranspiration (ETo), the total available moisture (TAM) and the readily available moisture (RAM) were calculated using the CropWat 8.0 software (©FAO 2009) according to Allen et al. (1998) and Doorenbos and Kassam (1979).
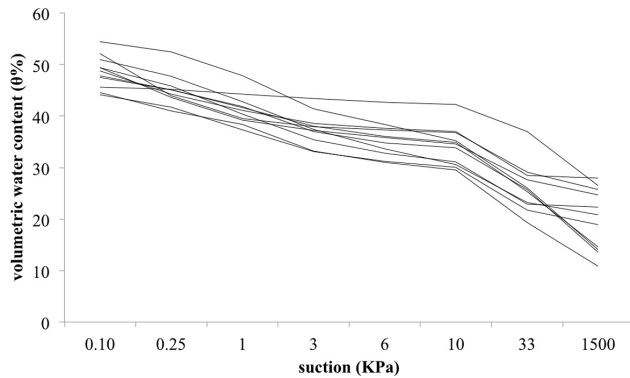
Figure 1. Water retention curves of sampled soils.
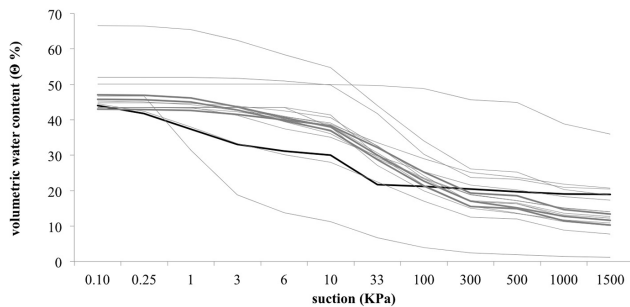
Figure 2. Sample 5: actual (black) and PTF water retention curves; the curves by Wösten et al. 1999 are highlighted.

3 Results

3.1 Soil

By the measurement of volumetric water content, it is possible to describe the water retention curve for all of the samples. Table 2 shows the measured volumetric water contents at the different suction values investigated and Fig. 1 shows their water retention curves. The water retention curves, with the exception of sample 8, display a similar trend. For suction values less than 10 kPa, the values are not very different, while in the end part – when the suction is high – there are some differences. The curve's slope increases from 10 to 33 kPa due to the different water extractor used – a sand box for 10 kPa and a Richards plate for 33 kPa.

As one of the study aims is to compare the landfill soil with a natural reference soil, in the first part of the paper, sample 5 is analysed. Sample 5 is the only landfill soil showing the same amount of organic carbon as the reference one.

Using sample 5 chemical–physical data as inputs of PTFs, the sample 5 predictive water retention curve is compared with the measured one. This comparison is shown in Fig. 2; in this Figure, the curves by Wösten et al. (1999)(PTFs applicable to Europe soils) are highlighted. From the comparison it clearly emerges that for suction values lower than 100 kPa, all PTFs except one overestimate the measured data, whereas

for suction values of 1500 kPa for 12 cases the measured value is higher than the predicted one.

To identify which of the authors, and thus of the models, are more accurate in describing the hydraulic behaviour of the landfill soils, samples of chemical–physical data are used as inputs of PTFs, so all water retention curves are developed and then the RMSE test was conducted (Fig. 3, Table 4). It emerges that the curve by Wösten al. (1999), showing a continuous pedotransfer function, is the closest to the measured data. The results of this test and the comparisons indicate a need to conduct studies to develop new parameter values which are able to describe the behaviour of degraded soils.

To compare natural soils with a reference one, reference soil water retention curves were developed using the PTFs. The reference soil water retention curve is described as the arithmetic mean of volumetric water content at different suction values obtained from processing PTFs. The sample 5 water retention curve is compared with the reference one (Fig. 4). This comparison reveals that the reference soil PTFs data always overestimate the measured data for all suction values lower than 100 kPa, whereas for suction values higher than 300 kPa, measured data are greater than the reference soil.

To compare the measured hydraulic properties of the landfill soil with the reference soil, their volumetric water contents – at suctions 0.10 kPa, at field capacity, at wilting point and the available water for plants – are compared. The histogram in Fig. 5 shows the water content at a suction of 0.10 kPa; soils have values similar to each other (average θ % is 48.61 %, SD 3.18 %), and also similar to the reference soil (θ % is 46.32 %).

The field capacity is described as the optimal relationship between water and air in the soil; this condition is verified when the micropore volume is entirely occupied by water while macropore volume is entirely occupied by air. In the literature the field capacity is represented by the water content at suction values in the range of 10 kPa and 33 kPa (10 kPa for sandy soil and 33 kPa for other soils). At field capacity (histogram Fig. 6), the sample soil average θ % is 26.05, SD 4.68 %; this value is lower than that of the reference soil (θ % is 30.16 %).

The histogram in Fig. 7 shows the soils at a suction of 1500 kPa (wilting point); the average of volumetric water content of soils sampled is θ % is 19.98 %, SD 5.97 %; the trend in this case is very variable, with one soil that has a water content of θ % = 27.91 % and another θ % is 10.86 %. The reference soil instead has a value of θ % is 13.66 %; in nine soils the water content is higher than that of the reference soil.

In general terms, the available water for plants is defined as the difference between soil water content at suction 33 kPa – soil water content at field capacity – and 1500 kPa – soil water content at wilting point (histogram Fig. 8). For the investigated soils the average amount of available water has a value of θ % = 6.06 %, very high SD 4.70 %, with a minimum
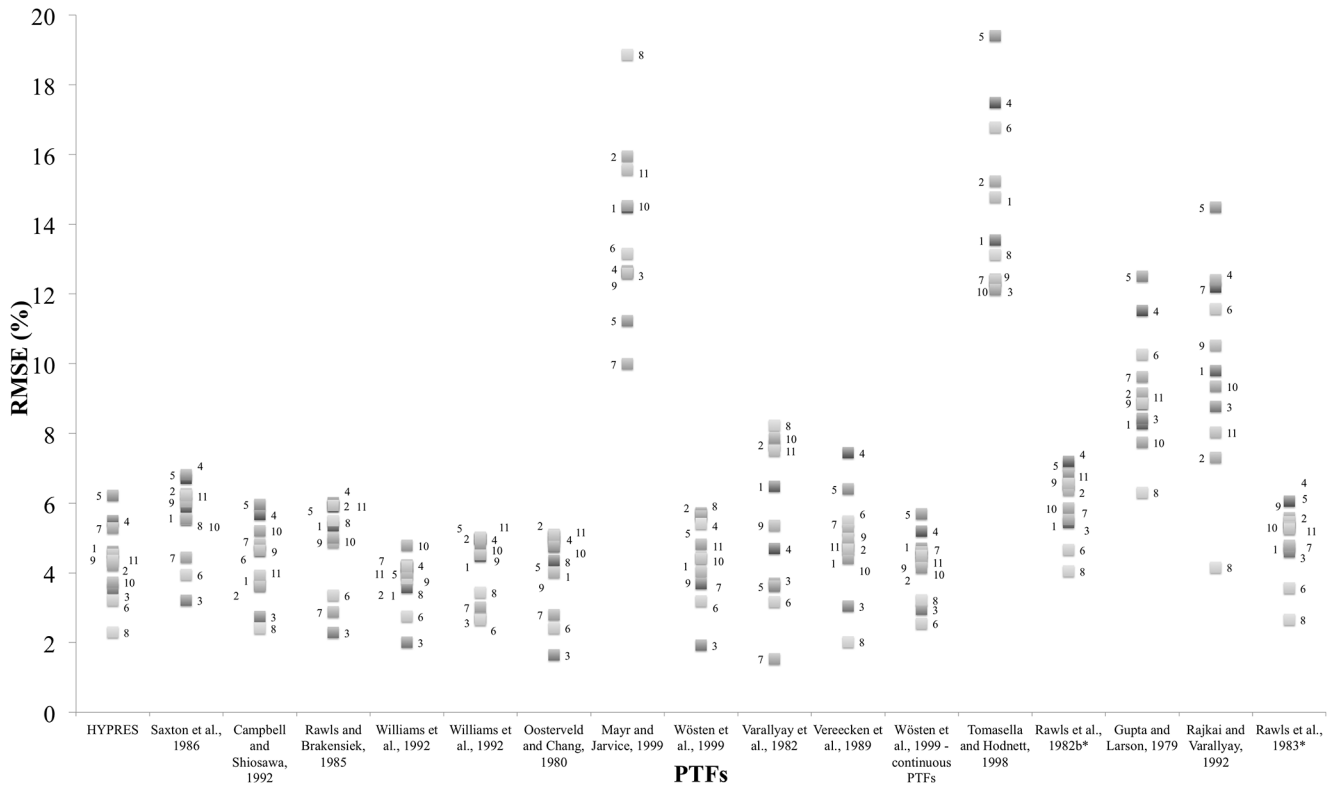
Figure 3. Matrix representing the result of the RMSE test – each pixel for a combination of the soil's PTF and RMSE.

Table 4. Results of the calculation of RMSE.

PTF	RMSE % (for samples)										
	1	2	3	4	5	6	7	8	9	10	11
HYPRES	4.6	4.2	3.6	5.5	6.2	3.2	5.3	2.3	4.5	3.7	4.4
Saxton et al. (1986)	5.9	6.3	3.2	6.7	6.8	4.0	4.5	5.6	6.0	5.6	6.2
Campbell and Shiosawa (1992)	3.7	3.6	2.8	5.7	6.0	4.6	4.8	2.4	4.7	5.2	3.9
Rawls and Brakensiek (1985)	5.4	5.9	2.3	6.0	5.9	3.4	2.9	5.5	4.9	5.0	5.9
Williams et al. (1992)	3.6	4.0	2.0	4.2	4.2	2.8	4.2	3.8	4.0	4.8	4.2
Williams et al. (1992)	4.5	5.0	2.7	5.0	5.0	2.7	3.0	3.5	4.5	4.8	5.0
Oosterveld and Chang (1980)	4.4	5.1	1.7	5.0	4.8	2.4	2.8	4.9	4.0	4.8	5.1
Mayr and Jarvice (1999)	14.5	16.0	12.7	12.6	11.2	13.2	10.0	18.9	12.6	14.5	15.6
Wösten et al. (1999)	3.7	5.7	1.9	5.7	5.6	3.2	4.5	5.4	4.0	4.8	4.4
Varallyay et al. (1982)	6.5	7.7	3.7	4.7	3.6	3.2	1.5	8.2	5.4	7.9	7.5
Vereecken et al. (1989)	4.8	4.7	3.1	7.5	6.4	5.5	5.2	2.0	5.0	4.4	4.7
Wösten et al. (1999)	4.7	4.3	3.0	5.2	5.7	2.6	4.6	3.2	4.5	4.2	4.5
Tomasella and Hodnett (1998)	13.6	15.2	12.2	17.5	19.4	16.8	12.4	13.1	12.4	12.1	14.8
Rawls et al. (1982b)*	5.5	7.1	6.5	7.2	6.8	4.7	5.9	4.1	6.4	5.5	6.6
Gupta and Larson (1979)	8.3	9.2	8.4	11.5	12.5	10.3	9.6	6.3	8.9	7.8	8.9
Rajkai and Varallyay (1992)	9.8	7.3	8.8	12.2	14.5	11.6	12.4	4.2	10.5	9.4	8.0
Rawls et al. (1983)*	4.7	5.4	4.6	6.1	5.6	3.6	4.8	2.7	5.5	5.3	5.3

* corrected for OM according to Nemes et al. (2009).

value of θ % = 0.55 % and a maximum of θ % = 12.14 %; the reference soil has a value of θ % = 16.50 %.

All the sampled soils have a much lower available water θ % than the reference soil, despite having an organic carbon content about twice as high as in the reference soil. Generally, high values of organic carbon correspond to high levels of organic matter, which enhances permeability and water availability in the soil. It would be interesting to study
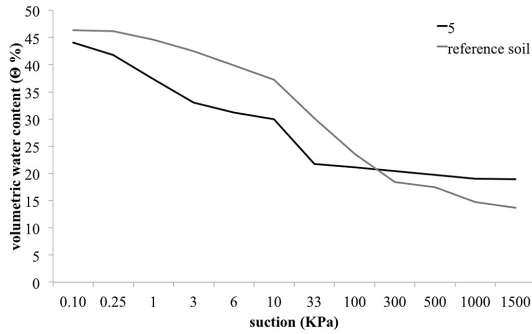
Figure 4. Comparison between sample 5 water retention curve and the reference curve – described as the arithmetic mean of PTFs values.
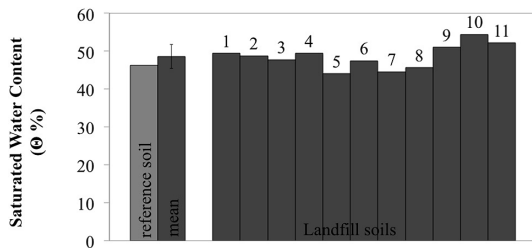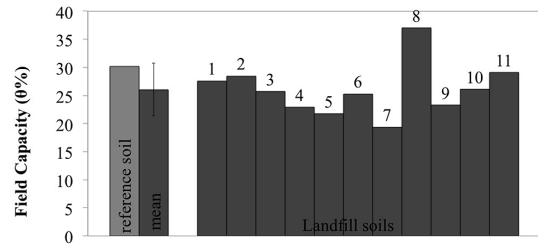

Figure 5. Volumetric water content (θ %) at suction 0.10 kPa: comparison between reference soil and landfill soils.

Figure 6. Volumetric water content (θ %) at field capacity: comparison between reference soil and landfill soils.
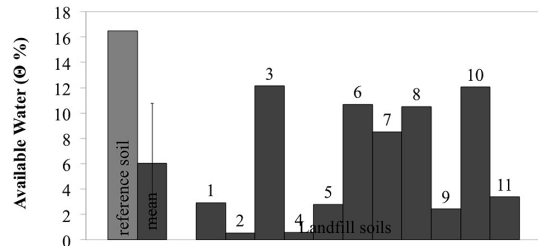
Figure 7. Volumetric water content (θ %) at a suction of 1500 kPa: comparison between reference soil and landfill soils.

Figure 8. Available water to plants (θ %): comparison between reference soil and landfill soils.

why a soil presenting characters of physical degradation i.e. compaction, associated with a lack of organic carbon content, has, on the contrary, a high organic carbon content. With this in mind, it would be interesting, also, to study the carbon decomposition in humic and fulvic acids in association with limestone content.

3.2 Flora and vegetation

The total number of plant species sampled amounts to 90 (see Appendix A); almost all of them are very common and abundant in the province of Piacenza (Bracchi and Romani, 2010; Romani and Alessandrini, 2001). Most of the species were found to be competitive–ruderal (43 %) and ruderal (13 %) (Grime, 2001) and belonging to the phytosociological class *Stellarietea mediae* R. Tx. Lohm. et PRSG. in Tx. 1950 which includes nitrophilous annual vegetation (Mucina et al., 1993; Oberdorfer, 1993; Ubaldi, 2008).
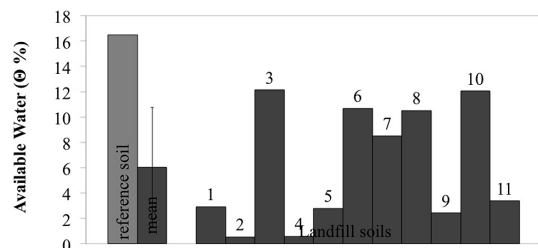
Table 5 shows a list of the flora biological spectrum. The study area has a particularly high percentage of therophytes (45 %) when compared to the values of the biological range of the province of Piacenza (23 %; Romani and Alessandrini, 2001) and Emilia-Romagna (28 %; Pignatti et al., 2001). Typically, ephemeral annual species tend to be concentrated in urban environments (Sukopp and Werner, 1983) and in Italy, regardless of human disturbance, their percentage increases gradually from north to south in response

to the emergence of a distinctly arid climate (Pignatti, 1994, 1976).

Fig. 9 represents the monthly rainfall and evapotranspiration and it should be noted that the ETo is greater than the rainfall in the period from May to August, indicating a summer drought.

The histogram referring to the *F* index (Fig. 10) shows that most of the species found require soils with a moisture content ranging from moderately dry to moderately moist. The typically xerophyte species and those found in submerged soils are absent, while there are two (*Bolboschoenus maritimus* (L.) Palla and *Eleocharis palustris* (L.) Roem. & Schult) that need wet soil.

In Fig. 11 the graphs referring to the amount of water lost from a common agricultural soil of medium texture 1 m deep (a), and the soil cover of the landfill (b) are presented, considering both the climatic conditions of Piacenza and the cover of grassland vegetation of perennial grasses (cool season grass varieties including bluegrass, fescue and ryegrass;

Table 5. Biological spectrum of flora.

	Biological spectrum of flora (%)
Therophytes	45
Hemicryptophytes	41
Geophytes	11
Phanerophytes	3
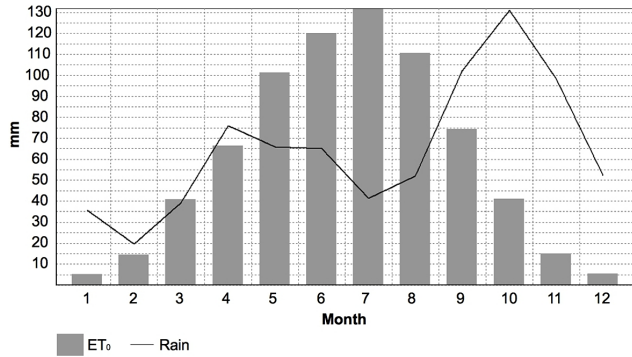
Figure 9. Monthly rainfall and evapotranspiration (ETo). Climate data source: San Lazzaro Alberoni weather station (Piacenza 1961–2005).

Figure 10. F index (soil moisture). Percentages are weighted by the frequency of the species in the monitoring sites (see column "Presence" in the Appendix). Legend: 1 is very dry, 1.5 is dry, 2 is moderately dry, 2.5 is fresh, 3 is moderately moist, 3.5 is moist, 4 is very moist, 4.5 is wet and 5 is flooded or submerged.
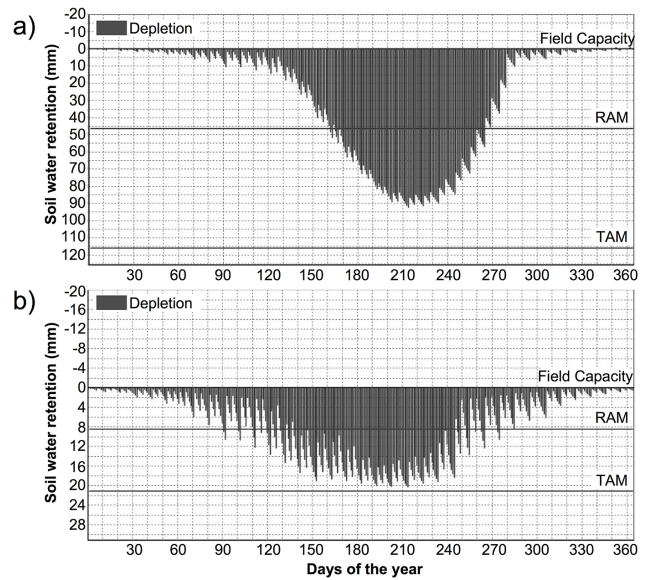
Figure 11. Water lost from agricultural soil (**a**) and from the landfill cover soil (**b**) by Crop Wat 8.0 software. Legend: RAM represents readily available moisture; TAM represents total available moisture.

Allen et al., 1998). The soil of the landfill has less water available to vegetation compared to agricultural soil.
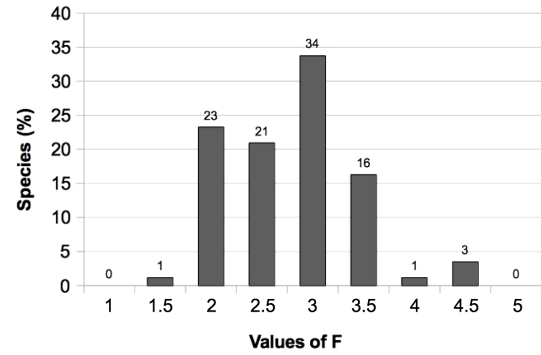
4 Discussion and conclusions

In this study, the attempt to relate the hydraulic properties of degraded soil with plant coverage is presented.

The hydrological properties of a degraded soil are described through a comparison between the laboratory tests and the results of predictive systems by PTFs, showing that the PTFs are not able to describe them.

The study of the hydraulic properties of landfill cover soils has outlined that these soils have less water content available in comparison with a natural reference soil; this is a characteristic of degradation.

On the basis of PTFs, some conclusions can be formulated. PTFs have the advantage of being relatively inexpensive and easy to derive and use, but for application at a specific point and for soils that are outside the range of soils used to derive them, prediction using PTFs might be inadequate. In this case, direct measurement is the only option (Wösten et al., 2001) and it can be interesting to conduct studies to develop degraded soils using new PTFs parameters and to relate them to the type of soil organic content. Generally, high values of soil organic carbon correspond to high levels of organic matter, which enhances permeability and water availability. With this in mind, it would be interesting to study why a soil presenting characters of physical degradation i.e. compaction, associated with a lack of organic carbon content, has, on the

contrary, a high organic carbon content. It would be interesting, also, to study the carbon decomposition in humic and fulvic acids in association with limestone content.

Analysing vegetation, it can be said that the landfill vegetation is mainly related to the soil character. The low water content, together with the lack of depth and compacted structure, would justify the current presence of a vegetation cover which consists predominantly of therophytes instead of a more developed and stable perennial vegetation with shrubs and trees, as observed for other landfills several years after their coverage (El-Sheikh et al., 2012; Huber-Humer and Klug-Pümpel, 2004; Rebele and Lehmann, 2002). The high frequency of therophyte does not seem to be justified by

summer drought and by the low level of human disturbance that affected the area in recent years, given that, under the same climatic conditions, the potential vegetation of the area should be represented by riparian forests of *Populetalia albae* Br.-Bl. 1935 (Puppi et al., 2010). These forests, although not very widespread, are present and contiguous to the landfill.

The presence of *Bolboschoenus maritimus* (L.) and *Eleocharis palustris* (L.), which need wet soil, is explained by the fact that F refers to soil water availability during the time of year when the species carry out their vegetative cycle (Landolt et al., 2010). In this case the above-mentioned hydrophilic plants were detected only in the spring months when the monthly evapotranspiration is less than or equal to rainfall.

In comparison with agricultural soil in the same climatic conditions, the landfill soil has less water available to vegetation, and this contributes to water stress for plants over a longer period (March to September) and is more pronounced as the amount of water absorbed by plants during the summer is close to their permanent wilting point (TAM line).

The low water content in association with high organic carbon, the lack of depth, the compacted structure of these soils and the current presence of a vegetation cover, which consists predominantly of therophytes, are important studied aspects of the aims of the New Life project, which seeks to establish a treatment for restoring degraded soils. This treatment – the reconstitution – produces a new soil, called reconstituted soil. The comparison between chemical-physical characters of degraded and reconstituted soil is very important. In this comparison it will be interesting to study their hydraulic properties in relation to their plant coverage.

Edited by: A. Cerdà

Appendix A

Table A1. Species, life form, *F* index, plant strategies and presence of the sampled plant.

n	Species	Life form	*F* index	Plant strategy	Presence
1	*Abutilon theophrasti* Medik.	T	2.5	cr	3/52
2	*Agrimonia eupatoria* L.	T	2	cr	2/52
3	*Allium* spp.	–	–	–	1/52
4	*Alopecurus myosuroides* Huds.	T	3	r	10/52
5	*Alopecurus pratensis* L.	T	3.5	cs	5/52
6	*Alopecurus rendlei* Eig	T	3	crs	7/52
7	*Amaranthus retroflexus* L.	T	2.5	cr	18/52
8	*Ambrosia artemisiifolia* L.	T	2	cr	15/52
9	*Amorpha fruticosa* L.	H	3.5	crs	1/52
10	*Aristolochia clematitis* L.	G	3.5	cr	2/52
11	*Arrhenatherum elatius* (L.) P. Beauv. ex J. and C. Presl	H	3	cr	21/52
12	*Artemisia vulgaris* L.	G	2.5	crs	13/52
13	*Atriplex patula* L.	T	2.5	cr	10/52
14	*Avena fatua* L.	T	2.5	cr	14/52
15	*Ballota nigra* L.	T	2.5	cr	4/52
16	*Bolboschoenus maritimus* (L.) Palla	T	4.5	cs	1/52
17	*Bromus hordeaceus* L.	T	3	cr	14/52
18	*Bromus sterilis* L.	T	2	r	30/52
19	*Capsella bursa-pastoris* (L.) Medik.	T	2	r	6/52
20	*Cardamine hirsuta* L.	T	3	rs	3/52
21	*Cerastium* spp.	–	–	–	9/52
22	*Chenopodium album* L.	T	2	r	27/52
23	*Cichorium intybus* L.	T	2.5	crs	2/52
24	*Cirsium arvense* (L.) Scop.	T	3	cr	6/52
25	*Cirsium vulgare* (Savi) Ten.	T	3	cr	1/52
26	*Convolvulus arvensis* L.	T	2.5	cr	50/52
27	*Crepis setosa* Haller f.	H	1.5	r	5/52
28	*Crepis vesicaria* L.	T	2	cr	2/52
29	*Cynodon dactylon* (L.) Pers.	T	2	cs	44/52
30	*Dactylis glomerata* L.	H	3	crs	6/52
31	*Dipsacus fullonum* L.	T	3.5	cr	1/52
32	*Echinochloa crusgalli* (L.) P. Beauv.	G	3.5	cr	3/52
33	*Eleocharis palustris* (L.) Roem. and Schult.	H	4.5	crs	2/52
34	*Elymus repens* (L.) Gould	T	3	cs	52/52
35	*Erigeron annuus* (L.) Desf.	H	2.5	cr	2/52
36	*Euphorbia cyparissias* L.	H	2	crs	1/52
37	*Galium aparine* L.	G	3	cr	8/52
38	*Galium verum* L.	H	2.5	crs	2/52
39	*Geranium dissectum* L.	T	3	cr	17/52
40	*Geranium molle* L.	H	2.5	cr	9/52
41	*Hordeum murinum* L.	T	2	r	23/52
42	*Humulus japonicus* Siebold and Zucc.	T	3.5	cr	1/52
43	*Hypericum perforatum* L.	G	3	crs	2/52
44	*Lactuca serriola* L.	H	2	cr	9/52
45	*Lamium purpureum* L.	T	3	r	7/52
46	*Lapsana communis* L.	T	3.5	cr	2/52
47	*Lepidium draba* L.	G	2	cr	3/52
48	*Lolium perenne* L.	H	3	cr	4/52
49	*Lythrum salicaria* L.	T	4	cs	1/52
50	*Malva alcea* L.	T	2.5	cs	2/52

Table A1. Continued.

n	Species	Life form	F index	Plant strategy	Presence
51	*Malva sylvestris* L.	T	2.5	crs	2/52
52	*Matricaria chamomilla* L.	H	3	r	2/52
53	*Medicago lupulina* L.	T	2	rs	3/52
54	*Medicago sativa* L.	H	2	cs	8/52
55	*Melilotus albus* Medik.	H	2.5	cr	3/52
56	*Mentha arvensis* L.	H	3.5	crs	2/52
57	*Myosotis arvensis* (L.) Hill	T	2	cr	2/52
58	*Onopordum acanthium* L.	T	2	cr	2/52
59	*Ornithogalum umbellatum* L.	H	3	crs	1/52
60	*Papaver rhoeas* L.	H	2	r	1/52
61	*Persicaria lapathifolia* (L.) Delarbre	H	2.5	cr	2/52
62	*Plantago lanceolata* L.	H	3.5	crs	8/52
63	*Poa pratensis* L.	T	3.3	crs	1/52
64	*Poa trivialis* L.	H	3.5	crs	14/52
65	*Polygonum aviculare* L.	T	3.5	r	23/52
66	*Portulaca oleracea* L.	H	2.5	r	1/52
67	*Potentilla reptans* L.	H	3	crs	3/52
68	*Ranunculus bulbosus* L.	H	2	crs	10/52
69	*Robinia pseudoacacia* L.	H	2.5	c	1/52
70	*Rumex crispus* L.	H	3.5	cr	44/52
71	*Rumex pulcher* L.	H	3	crs	5/52
72	*Salix alba* L.	T	4.5	c	1/52
73	*Salvia pratensis* L.	H	2	crs	2/52
74	*Solanum nigrum* L.	G	3	r	2/52
75	*Sonchus asper* (L.) Hill	H	3.5	cr	3/52
76	*Sonchus oleraceus* L.	H	3	cr	2/52
77	*Sorghum halepense* (L.) Pers.	H	2	c	2/52
78	*Stellaria media* (L.) Vill.	H	3	cr	14/52
79	*Tanacetum vulgare* L.	H	3.5	c	2/52
80	*Taraxacum officinale* Weber	G	3	crs	3/52
81	*Torilis arvensis* (Huds.) Link	H	2	cr	2/52
82	*Trifolium fragiferum* L.	H	3	crs	2/52
83	*Trifolium pratense* L.	G	3	crs	3/52
84	*Trifolium repens* L.	H	3	crs	4/52
85	*Valerianella* spp.	–	–	–	2/52
86	*Verbascum thapsus* L.	P	2.5	crs	4/52
87	*Verbena officinalis* L.	P	3	cr	8/52
88	*Veronica persica* Poir.	P	3	cr	15/52
89	*Vicia sativa* L.	T	3	cr	19/52
90	*Xanthium orientale* L. subsp. *italicum* (Moretti) Greuter	G	3	cr	4/52

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