IMPACT OF MINIMUM TILLAGE, OAT STRAW MANAGEMENT, AND CHICKEN MANURE ON SOIL WATER CONTENT, RUNOFF, EROSION AND TOMATO PRODUCTION

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Abstract

Sustainability of vegetable farms in south Uruguay depends on development of farming systems that can arrest soil deterioration. In a context where major constraints exist for irrigation, and rainfall is highly spatial and temporally variable, one of the main causes of yield reduction in deteriorated soils might be the reduction in soil moisture supply capacity. We established an experiment to determine the effect of different tillage systems on soil water content, runoff and erosion at high rainfall intensity, and on processing tomato (*Solanum esculentum*) yield. We report the results of the first year of the experiment set up in march 2010 at a fine silty Pachic Argiudoll, with four treatments: *Minimum Tillage with Cover Crop*, planting oat (*Avena byzantina)* in basins *and leaving it as mulch (MTCC)*; *Conventional tillage with Green manure*, same than previous treatment but oat biomass is incorporated to the soil through conventional tillage *(CTGM)*; *Conventional Tillage with Chicken Manure (CTChM);* and *Conventional Tillage (CT)*. Except CT, all other treatments incorporated chicken litter (7.0 Mg ha^{-1}).
Soil moisture was measured at 20 cm depth with time domain reflectrometry and at 100 cm depth with a neutron probe. Runoff and sediment loss were measured with a rainfall simulator at 6 mm/min rainfall intensity. Soil water content at 20 cm depth was the highest in the *MTCC* and lowest in *CTGM and CTChM*, yielding up to 10% more volume water content. Runoff and soil erosion was less at both treatments with oat, *MTCC and CTGM*. However, crop yield was the lowest at the *MTCC*, pointing out the need for extra attention to the fertilization scheme, because plants showed symptoms of N deficit at the beginning of the growth period. Minimum tillage with mulching contributed to conserve soil water, and to reduce soil runoff and soil erosion.

Introduction

Land degradation and poor soil fertility are major limitations to maintain vegetable production that makes an intensive use of the soil. Many smallholder farmers in southern Uruguay have specialized and intensified their production systems in order to maintain their family income as production costs increase and vegetable prices are maintained or decrease. These changes have accelerated the soil degradation process mainly due to increased tillage intensity, poor soil cover, negative soil organic matter balance, and high frequency of the same crops (1). Moreover, climate change and variability affect the country with more frequent extreme events, drought periods and higher rainfall intensities, and hamper even more the sustainability of the environment and farm systems. Hence, the combination of these factors enhances both erosion risk and crop water deficit, which become critical issues.

Two projects[1] at farm level aimed at re-design vegetable farm systems in southern Uruguay had as one of their pillars, the implementation of practices that could improve soil quality. The main practices implemented were: crop rotations, inclusion of a pasture phase when the farm size was big enough, incorporation of organic manures, and reducing plot sizes avoiding steep slopes.

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These practices reduced soil erosion, but they were not enough to reduce it to a level below the 7.0 Mg ha^{-1} $year^{-1}$ indicated as the tolerance level for these soils (2), when pastures could not be included in the crop system due to small farm area (3).

In fine textured soils with the presence of an argillic horizon with its upper limit at 20 cm on average, it is not feasible to produce vegetables with no till. In Uruguay, the majority of vegetable crops are grown on raised beds or in ridges. Under these conditions, minimum tillage with cover crops appears as a good low cost alternative. Conservation tillage was defined by the US Conservation Technology Information Center as "any tillage and planting system that covers at least 30 percent of the soil surface with crop residue" (4). In different crop systems, it has been proved that there is a relationship between retention of mulch and reduction of runoff and soil losses by erosion (5, 6). Cover crops left as mulch have also been observed to increase the infiltration and storage of rainwater up to 50% (7) and to reduce soil evaporation losses up to 52% (8).

In vegetable production, previous studies have demonstrated that the uses of minimum tillage combined with cover crops and raised beds can improve soil environment (9, 10). However, the impact on yield has been contradictory (11, 12, 13). In a study on a silt loam soil the authors (14) concluded that farmers should alternate between conventional and minimum tillage, to enhance soil quality while overcoming some disease and yield problems observed with continuous minimum tillage. In Uruguay, a similar study for vegetable crops comparing minimum with conventional tillage, showed potential benefits in terms of soil quality and soil moisture accumulation, while yields were not affected (15). Still, to achieve a significant impact in the adoption of this technology, more research that quantifies the benefits in terms of the production and environment are needed. Particularly, studies on the effects of different soil management strategies on runoff and soil moisture under vegetable crops grown in ridges on fine textured soils are scarce.

The aim of this study was to test the hypothesis that tillage reduction with cover crops in conjunction with application of chicken litter in vegetable crops grown in raised beds on a fine textured soil, would improve soil moisture availability to plants while reducing runoff when compared to traditional technologies. We established an experiment with four different soil management strategies with the following specific objectives: 1- to quantify the soil available moisture along the tomato crop cycle, 2- to quantify differences between treatments on the yields and water use efficiencies, and 3- to quantify the vulnerability to soil erosion under high rainfall intensities.

Materials and Methods

The experiment was run from March 2010 to March 2011, in a research station (CRS, South Regional Center – Faculty of Agronomy, Universidad de la República) in southern Uruguay, on a fine silty Pachic Argiudoll (Brunosol Eutrico Típico), 1% slope. Four treatments and three replicates were arranged in a complete random design. Treatments were: *Minimum tillage with cover crop (MTCC), Conventional tillage with green manure (CTGM)*, *Conventional tillage with chicken manure (CTChM),* and *Conventional tillage (CT)*, further explained in Table 1. Tomato (*Lycopersicum esculentum,* Loica variety) was transplanted on all four treatments the 22nd of October at a density of 26,666 plants ha^{-1}. Irrigation was applied only to avoid plant death at the transplant and during the growing face when the atmospheric demand was extremely high, (total water irrigated: 14 mm).

Table 1 Soil management detail for the four treatments

Date	Activities	MTCC	CTGM	CTChM	CT
3/3/10	Tandem disk + disc hiller	yes	yes	yes	yes
3/3/10	Chicken manure ($Mg.ha^{-1}$) incorporated with disc hiller	7.0	3.5	7.0	--------
3/3/10	Oat (*Avena Byzantina*) ($kg.ha^{-1}$)	120	120	--------	--------
--------	Control weeds with herbicide	--------	--------	yes	yes
7/9/10	Oat burnt with glyphosate	yes	yes	--------	--------
6/10/10	Oat incorporated ($Mg.ha^{-1}$) with disc hiller	--------	8.5	--------	--------
6/10/10	Chicken manure ($Mg.ha^{-1}$) incorporated with disc hiller	--------	3.5	--------	--------

Note: Quantities are in Dry matter basis

Surface soil moisture content was measured with a time domain reflectometer (TDR), and gravimetric samples multiplied by bulk density. Soil moisture from 20 to 40 cm depth was measured with a neutron probe, calibrated with gravimetric samples multiplied by bulk density. The moisture-tension curve was measured from undisturbed samples, and Brooks and Corey model used based on SWRC (16) best fitting (average r^2 of 0.98). Actual available water was calculated as the difference between the actual water content in each moment and water at wilting point. ET_0 was calculated with Penman Montieth equation, and then multiplied by the Kc for each crop stage according to Allen *et al*. (17) to calculate the potential ETc. Crop evapotranspiration (ET) was calculated as the sum of ET between consecutive soil water storage readings from transplant to end of harvest, following the methodology described by Boulala *et al.* (13). For each period, ET was calculated as the sum of rainfall, irrigation and the difference in soil water storage to 100 cm depth. Effective irrigation was calculated from the amount of water applied and multiplied by the efficiency of the system and the measured uniformity coefficient.

Runoff plots (1.5 x 3 m) were installed, but no runoff was detected. Because the measured soil moisture was always below the field capacity, drainage may be considered negligible. Weekly tomato yields were measured from 2-metre transects, which included 7 to 9 tomato plants. Water-use efficiency (WUE) was calculated as the ratio of yield and ET. Mini-rainfall simulations were performed, using an Eijelkamp mini rainfall simulator with four replicates per treatment. The simulations were repeated in two different dates: at the end of the crop cycle in February 2011, and at the beginning of the next crop cycle in December 2011 (in the second year of the experiment). We measured runoff volume and sediment loss weight produced by a 4-minutes rainfall (6 mm min^{-1} intensity) on a 0.650 m^2 surface. Climatic parameters were monitored with an automatic meteorological station situated 630 m apart from the plot. A pluviometer was also installed next to the plot to verify the total amount of precipitation.

The statistical analyses were performed using Genstat 14th edition (VSN International Ltd., Lawes Agricultural Trust, U.K.). The effects of treatments on soil moisture monitored at different depths were assessed by an analysis of variance for repeated measurements. Yield, fruit/plant, fruit weight, ET, unsatisfied demand, and water use efficiency results were analyzed by ANOVA. Multiple means comparisons were separated by Fisher's protected least significant difference (LSD) at significance level of $P < 0.05$. Runoff and sediments results obtained after the mini rainfall simulations were not normally distributed, even after performing transformations, so they were assessed with the Kruskall Wallis test. Contrast comparisons between groups of treatments with and without oat were made with the Mann-Whitney U test.

Results

Soil moisture

Soil management, date, and their interaction had a significant effect on soil moisture at 20 cm depth. To compare soil managements within a date, we looked at the least significant difference (LSD) of the interaction (α = 0.05) = 3.6 mm each 10 cm of soil, being the coefficient of variation (CV) 10.5%. Soil moisture at 20 cm depth was the highest in *MTCC* and lowest in *CTChM and CT*, yielding up to 24 mm water content of difference early in the season (Fig. 1).

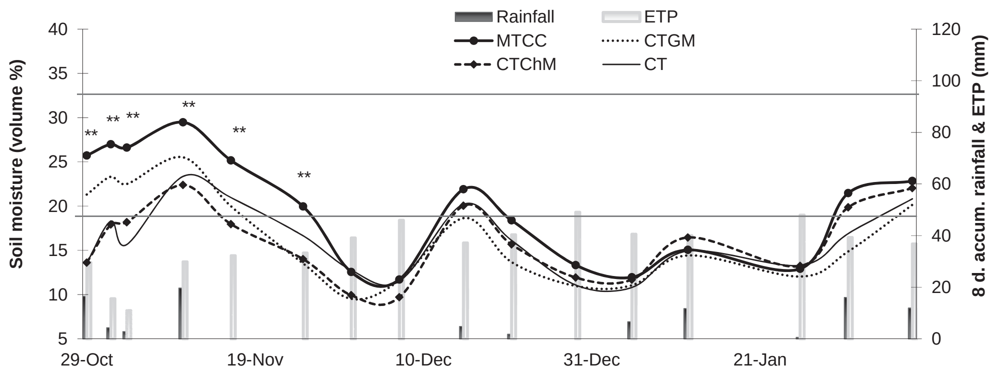

Figure 1 Soil moisture (volume %) to 20 cm depth under minimum tillage (*MTCC*), green manure (*CTGM*), chicken manure (*CTChM*), and conventional tillage (*CT*); and rainfall and potential ET accumulated from 8 days before each measurement, during the tomato crop cycle. Horizontal lines indicate water content at field capacity and permanent wilting point. **significant differences (α=0.05).

Soil moisture in the first 20 cm of soil was averaged per month and per soil management. Both factors, soil management and month, as well as their interaction had a significant effect, being LSD (α=0.05) = 3.6 mm, and the coefficient of variation = 5.8%. Soil moisture difference (averaged per month) between each of the Conventional Tillage treatments (*CTGM, CTChM*, and *CT*) and the Minimum Tillage (*MTCC*) is presented as a percentage of the potential available water, 42 mm to 20 cm depth (Table 2).

Table 2 Soil moisture differences in the first 20 cm of soil with respect to the minimum tillage (*MTCC*) averaged per month, during the tomato crop cycle. Values represent the soil moisture difference between treatments and *MTCC*, as a percentage of the potential available water

Treatments	Nov'10	Dec'10	Jan'11	Feb'11
CTGM	- 21.1 *	- 12.2 *	- 3.8	- 22.1 *
CTChM	- 38.6 *	- 2.2 *	2.3	- 5.8
CT	- 35.1 *	- 1.1	- 1.4	- 15.7 *

*significantly different from minimum tillage (α=0.05)
ANOVA for repeated measurements, Pr (>F): trat <0.001, month <0.001, month*treatment <0.001
CV (%)= 5.8, LSD (0.05) month*treatment = 3.6 mm

The same pattern was observed for actual available water content to 40 cm depth (Fig. 2), considering that the estimated soil moisture content at wilting point for this soil was 75 mm. ANOVA for repeated measurements results were, soil management p(F) = 0.002.; date*soil management p(F) <0.001; date p(F) <0.001. LSD date*soil management (0.05) = 8.1 mm, overall CV = 35.6 %.

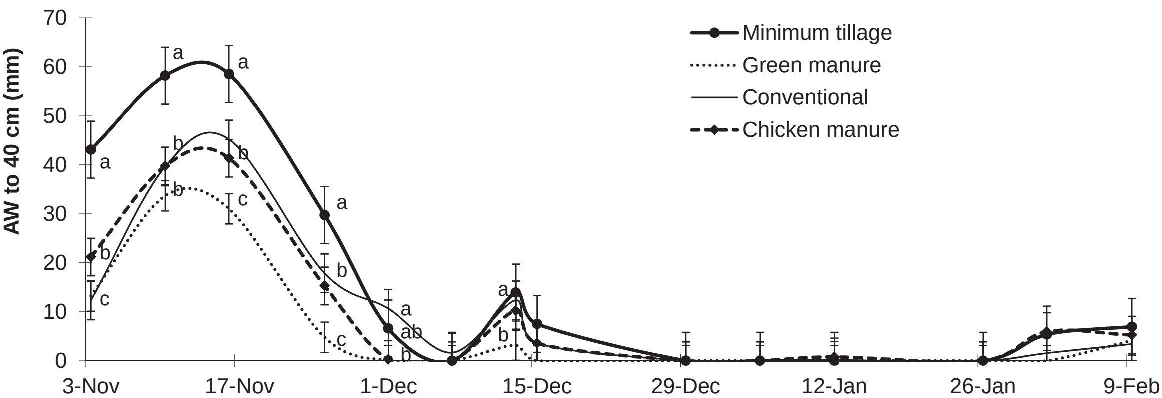

Figure 2 Available water content (mm) in the first 40 cm of soil monitored during the tomato crop cycle. Standard deviations are shown in bars, significant differences (α=0.05) among treatments are indicated by different letters.

Yield, evapotranspiration and water use efficiency
Crop yield, average number of fruits per plant and average fruit weight did not differ significantly among soil managements. While the first two showed a similar tendency, the average fruit weight was very similar in all soil managements (Table 3). At the beginning of the growth period, the plants under *MTCC* and *CTGM* showed symptoms of nitrogen deficit.

During the crop growth (22nd October to 17th February), the total amount of rainfall was 100 mm, and the highest rainfall intensity was 40 mm hr^{-1} during 15 minutes the 31st of January, when the soil was close to wilting point in the first 40 cm. No runoff was detected from runoff plots installed in the experiment. Consequently, it was assumed that all the rain and irrigation water infiltrated to the soil.

The ET calculated from the accumulated balance of soil moisture to 100 cm depth was the highest under the *MTCC*, giving up to 50 mm more water than the average of the other three treatments (Table 3). This resulted in a higher percentage of the estimated potential crop water demand (ETc) satisfied in *MTCC* (33%) compared to the rest of the soil managements (23 to 27%). The water use efficiencies calculated varied between soil managements, as well as within soil managements, which resulted in non-significant differences.

Table 3 Yield, number of fruits, fruit weight, accumulated ET and water use efficiency based on yield in the four treatments

Treat.	Yield (Mg ha^{-1})	Fruits/ plant	Fruit weight (g)	ET (mm)	Satisfied demand (%)*	WUEy (kg m^3)
MTCC	20.9	27.7	28.4	197.6 a	33 a	10.7
CTGM	26.7	34.0	29.4	144.8 b	24 b	18.4
CTCM	37.6	46.2	31.0	160.4 b	27 b	23.4
CT	31.2	38.4	30.0	138.1 b	23 b	23.4
C.V.	24.9	19.5	13.7	9.2	2.8*	31.3
Pr (>F)	0.11	0.07	0.87	0.005	0.005	0.09
LSD				27.8	0.17*	

* Log normal transformation was performed to run the ANOVA and LSD Fisher's protected multiple comparison test, means were transformed again to percentage for presenting the results. Significant differences (α=0.05) among treatments are indicated by different letters.

Runoff and sediments

When simulated rainfalls of 24 mm were applied at a rate of 6 mm/minute, soil moisture range at 0 -10 cm (volume %) was 9 to 11% in February 2011, and 18 to 24% in December 2011. The Kruskall Wallis test gave no difference in the post-hoc when multiple comparisons were performed. However, the trend was consistent for the four variables; the order from lower to higher runoff and sediments was: *MTCC* < *CTGM* < *CTChM* < *CT*. The contrasts between soil managements with oat (*MTCC* and *CTGM*) and without oat (*CTChM* and *CT*), showed a lower amount of runoff and eroded sediments for the first group, on both dates (Table 4).

Table 4 Median runoff and sediments from mini rainfall simulations

Date	February 2011		December 2011	
Contrast	Runoff (mm)	Sed. (kg/ha^{-1})	Runoff (mm)	Sed. (kg.ha^{-1})
MTCC & CTGM	0.1 a	20.0 a	0.7 a	120.8 a
CTChM & CT	10.5 b	1683.8 b	13.7 b	7073.8 b
U; p*2	5.0; 0.001	2.0; <0.001	0.0; 0.001	0.0; 0.001

Note: Significant differences (α=0.05) among treatments are indicated by different letters.

Runoff percentages of the total simulated rainfall were 6% on both dates for soil managements with oat, and 34% in February and 54% in December for the other two soil managements.

Discussion

Summarizing the main results, available water content was the highest in the minimum tillage, principally at the beginning of the crop cycle, in concordance the water balance was more favorable for the minimum tillage than for the other soil managements. Runoff and soil erosion measured with the mini rainfall simulator was lower at treatments with oat (*MTCC* and *CTGM*) than at treatments without (*CTChM* and *CT*). However, crop yield was the lowest at the *MTCC*. In the following paragraphs we will discuss this apparent contradiction.

Soil moisture

The *MTCC* caused a significant increase in soil available water content and moisture supply capacity. At the top 20 cm, available water content under *MTCC* was from 21 to 38% more than in the other treatments (Fig. 1 and Table 2). During the first forty days after transplant, the fruit set is defined and a water deficit may cause significant reduction in yields. During this period the water available for crops accumulated to 40 cm depth was on average 31% more in the *MTCC* when compared to the rest of the treatments (Fig. 2). At the beginning of December, when the crop reaches its maximum LAI, transpiring and drying the soil to permanent wilting point, the differences among treatments disappeared. Initially the idea was not to irrigate in order to capture the differences between treatments in relation to soil moisture. Because the soil moisture was always below the field capacity or even below wilting point in some moments, irrigation was given to avoid plant death. The potential maximum available water content to 40 cm depth was 172 mm, and, the available water content at this depth, never surpassed 50% of that value (Fig.2). From the end of December to the end of January, the soil in the top 40 cm was always dryer than permanent wilting point. Despite this fact, the crop was able to survive due to two reasons: it was able to extract water from depths deeper than 40 cm, which was shown by the decline in soil moisture content till the full depth (1 m) monitored during the crop growth period, and because of the strategically applied irrigations.

The percentage of soil coverage by residues was above 90% until the end of the crop cycle, probably due to the dryness of the season. Because of the high surface coverage by residues, the direct evaporation to the atmosphere in the *MTCC* might have been less than in the other soil management with significantly lower soil coverage (8). Since no runoff was detected (from runoff plots), the difference in soil moisture among soil managements is explained due to a reduced evaporation from the soil under the mulch , and higher infiltration rates, which allowed more moisture to be accumulated in the profile.

Yield, evapotranspiration and water use efficiency

Although the ET calculation presented is a simplification of the process actually occurring in the root zone, below the root zone and in the soil surface, it gives an idea of the different amounts of water that were delivered from the soil to the crop and atmosphere under different soil managements.

The total amount of rainfall from the beginning of November to the end of February was 60% less than the historic median rainfall for the period (calculated from data of the INIA Las Brujas meteorological station, Lat: 34° 40’ S - Lon: 56° 20’ W). All treatments were far from satisfying the estimated total crop water demand of 603 mm. This is probably the main reason for the general reduction of yields in our experiment compared to attainable yields for the region (18). The same variety yielded on average 95.6 Mg ha^{-1} in an experiment on INIA Las Brujas (19). However, our yields were close to those obtained on average by farmers. Average reported yields between 2006 and 2008 from farms within our region were between 25.7 Mg ha^{-1} and 42.2 Mg ha^{-1} (18). The soil moisture is one of the factors that explain the tomato yield in a linear positive relation. Processing tomato (var. Loica) yields obtained by farmers of the region in 2008 were linearly related to water deficits (20). The author reported yields as low as 25 Mg ha^{-1} when water deficit was 300 mm, to 75 Mg ha-1 when water deficit was 100 mm. Nevertheless, the opposite trend was found in our experiment: more water content, less yield. The trend of depleted yields observed under *MTCC* and *CTGM*, could be explained by other factors. First, we observed that plants in these two soil managements suffered more during the transplant. The lack of experience of workers transplanting in a situation with high amounts of mulch resulted in that some of the plants were found to be planted on a bubble of air. The visually more compacted soil under the mulch may also have influenced. As a consequence some plants could not survive. On top of that, we did not fulfill the extra nutrient requirements due to microbe immobilization that occur when green manures are used, even as mulch (10). This last fact was visually corroborated as plants showed symptoms of N deficit at the beginning of the growth period.

The actual evapotranspiration calculated as the accumulated changes in water storage plus irrigation showed that the *MTCC* evaporated an amount equivalent to the accumulated rainfall (100 mm) + irrigation (14 mm) + the initial amount of available water in the soil to 100 cm (99 mm). The rest of the soil managements had initially less available water in the soil profile: 61 mm the *CTGM*, 64 mm the *CTCM* and 30 mm the *CT*, reflecting a lower capacity to capture rainwater, both due to lower infiltration and higher evaporation. This is in agreement with the literature (6, 7, 8 and 15). The difference of water evapo-transpired between *MTCC* and the rest of the treatments was on average 50 mm, which could mean approximately 625 m^3 of water savings per hectare (considering the irrigation efficiency * uniformity coefficient = 0.8).

Water use efficiencies (WUE) values were in the range of those cited in the literature for tomato crop (21, 22, and 23). The tendency of lower water use efficiency for *MTCC* was the result of the tendency of lower yields obtained with more accumulated evapotranspiration for this treatment compared with the three other treatments. Irrigation WUE values from 17 to 24 kg m^{-3} were reported for arid regions when 50% of the total potential ETc demand was covered (23), while lower WUE values (10 to 17 kg m^{-3}) were reported when 100% of the ETc demand was covered. In our experiment, we were far below the 50% of potential ETc demand covered for the four treatments, but the treatments followed exactly the opposite trend: higher WUE were found under *MTCC* with the ETc demand satisfied to a larger extent. This demonstrates that in our experiment, the water was not the limiting factor for achieving higher yields. If that had been the case, we would have found a positive relationship between the soil moisture and the yields. As mentioned above, a failure to adapt transplant techniques due to the presence of cover crops and to fulfill nutrient deficits at the beginning of the cropping phase would probably explain the reduced yields and WUE under the *MTCC* treatment. Our results were similar to what was found by (13), where the permanent bed system did not improve WUE.

Runoff and sediments

The fact that not statistical differences were found for these variables in the multiple comparison test, in spite of the clear trend, was explained by the large variability within treatment. For future research, more replicates should be considered. Our study demonstrates that, even under high rainfall intensities, both at the end and at the beginning of the crop cycle, soil managements including cover crops left as mulch or incorporated, were able to reduce the amount of runoff and erosion to a high extent. For these soil managements, runoff percentages of the total simulated rainfall were maintained low in both dates; while for the soil managements without cover crops, this percentage was higher and different between dates. In the second date, the soil was wetter, which explained the higher runoff obtained (Table 4).

Conclusion

Minimum tillage with mulching contributed to increase soil water content, and to reduce soil runoff and soil erosion. This technique needs to be further adjusted in order to overcome nutrient deficits and reduced yields. We conclude that while minimum tillage with a cover crop has a big potential to reduce irrigation requirements and mitigate erosion risks, the introduction of this strategy also involves big changes regarding other aspects of conventional techniques. These include fertilizer use, management of cover crops before transplanting, and successful establishment of transplants into cover crops with minimum disturbance of surface residues and surface soil. This is thought to be better achieved in conjunction with farmers, in a fully co-participatory approach.

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Keywords
Conservation horticulture, minimum tillage, mulching, planting basin, soil water