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Article

Conservation Agriculture in Trouble? Estimating the Economic Impact of an Eventual Glyphosate Prohibition in Spain

Agricultura de Conservação em Dificuldade? Estimando o Impacto Econômico de uma Eventual Proibição do Glifosato na Espanha

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ABSTRACT - Weed control is a crucial aspect in many conservation agriculture systems given that costs and time savings from avoiding tillage are closely linked to the use of effective and environmental friendly herbicides. This has led to the widespread use of glyphosate in farms, as it is a broad-spectrum, easily degradable, low- cost herbicide. The recent debate on the safety of glyphosate and on the excessive use of chemical herbicides in food production has caused concern on farmers about the possible economic effects of a virtual ban on glyphosate. The aim of this paper is to estimate the costs associated with an eventual prohibition of glyphosate in Spanish conservation agriculture areas. The costs of different alternative weed control strategies for herbaceous and tree crops were calculated: i) substitution of glyphosate in chemical control; ii) minimum tillage; iii) conventional tillage; and iv) natural or planted vegetal groundcovers. The results show that banning glyphosate would increase the costs of chemical control by 40% for herbaceous and by 57% for tree crops. However, conventional tillage would be a cheaper option for herbaceous because costs increase by 10% compared to current techniques. Our estimations suggest that the ban on glyphosate would have a negative impact on the economic profitability of farms and also on other non-economic advantages derived from conservation farming techniques.

Keywords: conservation systems, conventional tillage, economic evaluation, weed control.

RESUMO - O controle de plantas daninhas é um aspecto crucial em muitos sistemas de agricultura de conservação, uma vez que os custos e a economia de tempo de evitar o plantio direto estão intimamente ligados ao uso de herbicidas eficazes e ecologicamente corretos. Isso levou ao uso difundido de glifosato em fazendas administradas sob agricultura de conservação, por ser um herbicida de amplo espectro, facilmente degradável e de baixo custo. O recente debate sobre a segurança do glifosato e sobre o uso excessivo de herbicidas químicos na produção de alimentos causou uma crescente preocupação dos agricultores sobre os possíveis efeitos econômicos de uma proibição virtual do glifosato. O objetivo deste trabalho é estimar os custos associados a uma eventual proibição do glifosato nas áreas de agricultura de conservação espanhola. Os custos de diferentes estratégias alternativas de controle de plantas daninhas foram calculados para herbáceas e árvores: i) substituição do glifosato no controle químico; ii) cultivo mínimo; iii) plantio convencional e iv) coberturas vegetais naturais ou plantadas. Os resultados mostram que a proibição do glifosato aumentaria os custos do controle químico em 40% para as culturas herbáceas e em 57% para as culturas de árvores.

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No entanto, a lavoura convencional seria uma opção mais barata para herbáceas, já que os custos aumentam em 10% com relação às técnicas atuais. Nossas estimativas sugerem que a proibição do glifosato teria um impacto negativo na lucratividade econômica de fazendas administradas sob a agricultura de conservação e também em outras vantagens não econômicas decorrentes de técnicas de agricultura de conservação.

Palavras-chave: sistemas de conservação, preparo convencional, avaliação econômica, controle de plantas daninhas.

INTRODUCTION

Conservation agriculture (CA) is often proposed as an alternative to conventional tillage and is based on practices that alter soils as little as possible. From an environmental point of view, conservation agriculture is recognized as an activity that improves soil and water quality, reduces erosion and also reduces the impact of the agricultural sector on greenhouse gas pollution (Hobbs, 2007). In addition, these practices represent significant time and direct cost savings for machinery and fuels, making them more economically profitable alternatives (Kassam et al., 2012).

The introduction and development of CA in Europe have been slow and relatively recent compared to other countries in North and South America, where these systems began in the early 1990s and now cover about 22% of the total arable land in the USA, 40% in Brazil and Canada, and 75 % in Argentina (Aquastat, 2016). In Europe, the CA expansion began in 2005, but the share of arable land remains low in most countries. Russia, Spain and Ukraine accumulate the higher areas, but with portions of their total arable land still less than 10%.

Global support for the CA in literature is strong. Studies supporting the environmental benefits of CA adoption are abundant (e.g. Martínez and Francia, 2006; Carbonell Bojollo et al., 2008; Sanz-Cobena et al., 2017 examine the effects on soil humidity, soil fauna, water quality and greenhouse gas emissions under Spanish conditions). Some economic studies on the cost and time savings associated with CA under Spanish climatic and soil conditions confirm that the profitability of these systems is higher than conventional due to reduced machinery costs, less dependence on fuel and time savings (Gil and Blanco, 2006; González-Sánchez et al., 2010; Arnal, 2010). However, the good performance of some CA systems is related to a high dependence on glyphosate and other chemical herbicides to control weeds, which implies a higher risk of herbicide resistance and other control problems (Giller et al., 2009).

Soil and climate conditions, together with environmental and economic advantages, have favoured the rapid expansion of CA systems in Spain. The total Spanish area under no-till (direct sowing) has been doubled since 2009 to 546,859 ha in 2015 (7.7% of the total area under arable crops) (Magrama, 2015). Winter cereals in rainfed areas and rotations including corn or sunflower as a second crop in irrigated fields are the main crops under CA techniques. In addition, the area of perennial tree crops under the CA system has increased by 30% since 2006, currently covering 4,190,000 ha (84% of total tree crops). The most common techniques are minimum tillage with 2,071,373 ha mainly in olive and vineyards, groundcovers with 1,200,000 ha especially for citrus and other fruits, and non-tillage with 458,000 ha, also for olive and citrus. Moreover, there are 1,022,114 ha of fallow managed under CA (44% under minimum tillage and 55% with groundcovers).

Weed control in conservation systems depends to a large extent on the proper use of crop rotations, as well as chemical herbicides that are effective and of low environmental impact in order to replace the common mechanical control of conventional agriculture. This has led to the widespread use of glyphosate, as it is a broad-spectrum, low-cost, easily degradable herbicide with little tendency to generate resistance (Heap, 2018).

In March 2015, the Health Organisation's International Agency for Research on Cancer (WHO-IARC) stated that glyphosate is "probably carcinogenic to humans" in a controversial Monograph (International Agency for Research on Cancer-IARC, 2015). Although a subsequent report of the Joint FAO/WHO Meeting on Pesticide Residues (JMPR, 2016) in May 2016 contradicted the first statement, the debate on the excessive use of chemical herbicides in food production and the safety of glyphosate has intensified in the social arena. In response, some local administrations in Spain (Madrid, Barcelona, Sevilla and Zaragoza among others) have decided to ban the use of glyphosate for weed control in public parks. Although the European Union decided in May 2016 to approve the use of glyphosate in agriculture for the next seven years, farmers' concern about the possible economic effects of a virtual prohibition of glyphosate is emerging.

Weed control is a crucial aspect in the implementation of conservation systems, as the cost and time savings involved in avoiding tillage are also related to the use of effective and environmentally friendly herbicides. The elimination of glyphosate in weed control could negatively affect the economic outcomes of CA farms and also increase the complexity and time requirements of field management, preventing the adoption of conservation systems by farmers.

The aim of this paper is to estimate the economic effects of a possible ban on the use of glyphosate in Spanish CA farms. Different control strategies are evaluated and a hierarchy based on their cost is established. It is particularly important to assess to what extent the economic benefits of conservation systems remain in a glyphosate ban scenario and how it might affect the timing and organisation of work in the fields. This study provides an estimate of these impacts and contributes to the debate on the most appropriate strategies for the farmer under the virtual glyphosate prohibition.

Finally, although not considered here, in addition to the costs associated with agricultural systems, attention must be paid to the effects on weed control in public parks and gardens, the cleaning of roads, irrigation canals and railways, where glyphosate is also used as the main herbicide.

MATERIAL AND METHODS

The economic impact of the glyphosate ban will be evaluated by calculating the costs under the current field weed control methods and comparing them with the control costs resulting from replacing glyphosate by alternative controls (chemical or mechanical). Herbaceous and perennial tree crops are evaluated separately.

In the case of herbaceous crops, the common management of winter cereals in conservation agriculture is considered. The most important regions for winter cereal in Spain are in Castilla-León, Castilla-la-Mancha and Aragón with 72% of the total cereal area, especially wheat and barley. Direct sowing techniques are mainly used in Castilla-León and Aragón, with more than 48% of the total Spanish area under this system (Magrama, 2015). In these regions, rainfed fields often incorporate crop rotations to obtain adequate weed control and better soil fertility management. The two-year rotation considered for our purpose is wheat-pea-barley-rape. In the case of irrigated fields, the conservation systems usually include winter cereal-corn (or sunflower) rotation, although in this case the application of herbicides after the cereal harvest is not necessary because the Spanish climatic conditions in summer (hot and dry) prevent the germination of weeds. Therefore, the estimates concentrate in this typical rainfed rotation. In the case of perennial crops, the cost estimate is based on data from a fruit tree farm managed as described later in this section.

For both type of crops, the costs (in € ha^{-1}) only include sowing and weed control operations. It does not include the costs of fertilization, harvesting and other necessary treatments against other pests or diseases. This approach isolates the effect of glyphosate removal. The selection of the appropriate equipment for each system and crop, as well as the time costs associated with its use, was carried out using the Barrio and Rebate (2016) and Magrama (2016) tools and following the ASABE (American Society of Agricultural and Biological Engineers) method. Therefore, the cost of machinery time includes fixed costs (depreciation, storage, interest, insurance and taxes) and variable costs (fuel, maintenance and repair of equipment). Given the specific characteristics of the field under consideration, medium sized equipment was selected according to the Magrama (2016) definition and following the guidelines of the IDAE (2009) and other studies for Spanish conditions (Arnal, 2010). In all scenarios the use of own machinery is considered acquired at 2016 prices. The labour costs were obtained from Magrama (2014).

Herbaceous crops

Two CA models are defined as the starting point for the analysis of herbaceous crops: minimum tillage and no-tillage (direct sowing). Although both systems replace deep tillage at pre-sowing with the application of glyphosate, under the minimum tillage a combination of cultivator-roller and conventional seed drill is usually used, while under the direct sowing system a special direct seed drill is required. In both cases the application of herbicides in post-emergency is used when new weeds emerge. Herbicides were selected considering the most common weed species in each system and in each crop of the rotation (INTIA, 2017).

The alternatives to the application of glyphosate consist of substitution by other herbicide treatments at pre-sowing (T1 and T2 programs) or by conversion to conventional system, which is based in mouldboard ploughing techniques followed by the use of cultivator-roller-conventional seed drill. Table 1 of the Annex includes a description of the herbicide programs, ingredients, doses and market prices for each crop in the rotation and for the three systems considered. In the case of CA systems (minimum tillage and direct sowing) the number of applications of glyphosate in pre-sowing can be 1 or 2 depending on the specific conditions of the field and year, so we have considered an average of 1.5-passes. In addition, two more herbicide treatments are usually applied in the early or late post-emergence of the crop trying to combine different active matters to effectively control weeds and avoid resistance. However, it should be noted that in the rotation considered, it is expected that there will be not serious problems with any species. The proposed active ingredients should achieve effective weed control.

The T1 and T2 alternative chemical programs are designed by replacing glyphosate with glufosinate or diquat in wheat, pea and barley, and napropamide in rape, assuming that the same 1.5-pass would achieve similar levels of weed control as glyphosate. In a conventional system, chemical treatments would only be necessary after sowing since the use of deep tillage at pre-sowing is the alternative to glyphosate. Table 2 in the Annex shows the relevant information on the equipment used (tractor and implements), the working time of each operation, the cost of working time and the market prices used in all scenarios with the crop rotation designed for herbaceous crops. The most important difference between the systems is the time required for tillage which is 30% higher in the minimum tillage compared to the direct sowing method and 127% higher in conventional tillage.

Perennial crops

The calculation of the costs for perennial tree crops is based on a real fruit plantation of 1 ha, with a distance of 3.5 m between rows of trees. The time needed for each operation is calculated assuming that only one pass treatment (chemical or mechanical) between rows is required. Therefore, the total distance to be covered in each management operation of one hectare is 2,857 m (10,000 m^2 divided by 3.5 m). When the weeded area is only the rows of trees 60 cm will be treated on both sides of the row (1.2 m). The total number of working hours for each operation will vary depending on the number and pass speed of the machinery and implements used in each scenario (distance divided by pass speed). The time resulting from this calculation will be increased by 20% to take into account the time lost when turning the end of each row and going to the plot.

To compare the economic costs of each alternative, a baseline scenario will be defined that considers the common management of perennial crops in a no-till system based on the exclusive use of chemical herbicides, especially glyphosate.

Baseline scenario: the herbicides commonly used in pre-emergence and early post-emergence are glyphosate combined with MCPA (2-methyl-4-chlorophenoxyacetic acid) to control dicotyledonous species and also a glyphosate treatment in September-October to control later emergencies in summer. With regard to application costs, it is necessary to take into account the use of a suspended boom sprayer, the tractor and the labour costs (tractor driver).

Several mechanical and chemical alternatives for glyphosate-free weed control are defined, including the following alternatives:

Table 1 - Herbicide programs, doses and market prices for each system and crop

Herbicide programs	Doses (L ha^{-1})	Price (€ L^{-1})	Crops											
			Wheat			Pea			Barley			Rape		
			MT	DS	CT	MT	DS	CT	MT	DS	CT	MT	DS	CT
Herbicide ingredients at pre-sowing														
Glyphosate 36% (1.5 pass)	2	10.00	x	x		x	x		x	x		x	x	
Herbicide ingredients at post-sowing														
Diflufenican (2.5%) +Chlortoluron (40%)	0.3	11.08	x		x									
Iodosulfuron-methyl-sodium (0.6%) + mesofulfuron-methil (3%)+ mefenpir-dietil (9%)	400*	103.50**	x											
Pendimethaline (40%)	5	9.92		x		x		x						
Cycloxydim (10%)	2.5	35.15				x	x	x						
Pendimethaline (30%)+Chlortoluron (25%)+Diflufenican (4%)	2	20.44							x	x				
Pinoxaden (6%)	1	67.10							x	x				
Clethodim (24%)	0.4	36.05										x	x	x
Metazachlor (50%)	2	42.32										x	x	x
Florasulam (2,28%)	275*	227.27**		x										
Bentazon (87%)	1150*	46.54**					x							
Fluroxypyr (20%)	1.5	27.00			x									
Isoxaben (50%)	0.2	71.87									x			
Diclofop (36%)	1.5	17.00									x			
Alternative herbicides at pre-sowing														
Treatment T1 Glufosinate (15%)	4	27.17	x	x		x	x		x	x				
Napropamide (45%)	3	29.35										x	x	
Treatment T2 Diquat (20%)	3	27.18	x	x		x	x		x	x				
Napropamide (45%)	3	29.35										x	x	

Percentage in brackets refers to active matter of each ingredient. MT: minimum tillage, DS: direct sowing, CT: conventional tillage.*doses in g ha^{-1}, ** price in € kg^{-1}.

Table 2 - Equipment characteristics, time cost and working time by agricultural system in herbaceous crops

Operation	Equipment characteristic*	Time cost (€ h^{-1})	Working time ($h\ ha^{-1}$)		
			Min. tillage	Direct sowing	Conventional till.
Various	Tractor 120 CV (100000 €)	29.61	1.55	1.19	2.71
Various	Tractor driver	11.60	1.55	1.19	2.71
Herbicide application at pre-sowing	Sprayer 16 m (9000 €) (1.5 passes)	24.24	0.24	0.24	-
Soil tillage and sowing	Cultivator+roller+conventional till seed driller 4 m (12000 €)	27.14	0.99	-	0.99
Soil preparation	4 blades mouldboard plough 14'' (10000 €)	22.02	-	-	1.40
Direct sowing	No-till seed driller (4 m) (50000 €)	41.20	-	0.63	-
Herbicide application after sowing	Sprayer 16 m (2 passes)	24.24	0.32	0.32	0.32

* In brackets market price of equipment and number of passes.

Herbicide treatments without glyphosate: combine herbicides from different groups that avoid repeating the same mode of action. The active ingredients and doses of this scenario were selected according to the recommendations of Saavedra et al. (2012, 2014).

In this chemical control scenario three alternative herbicide programs (T1, T2 and T3) are proposed with three annual applications. Table 3 of the Annex describes the programs designed for the chemical scenarios, including the current baseline treatment. However, additional applications may be necessary to compensate for an active ingredient as powerful as glyphosate, so the data calculated here would increase. The machinery and labour costs of this scenario coincide with those of the baseline scenario (sprayer+tractor+tractor driver).

Table 3 - Herbicide programs, doses and market prices in perennial crops

Herbicide program	Doses ($L\ ha^{-1}$)	Price (€ L^{-1})
Baseline scenario (no-till)		
Glyphosate (18%)+MCPA (18%) (2 passes)	4	5.97
Glyphosate (36%)	3	10.00
Treatment T1		
Oxyfluorfen (48%)	2	20.00
Glufosinate (15%)	3	27.17
Amitrol (24%)	6	8.56
Treatment T2		
Flazasulfuron (25%)	0.2	737.84
Fluroxypyr (20%)	1.5	27.00
Glufosinate (15%)	3	27.17
Treatment T3		
Diflufenican (50%)	0.7	44.00
Fluroxypyr (20%)	1.5	27.00
Glufosinate (15%)	3	27.17

Mechanical control: chemical control is partial or totally replaced by mechanical controls. Minimum tillage and conventional tillage will be considered within this alternative. Under the minimum tillage system chemical control is partially maintained by adding superficial tillage of the soil to eliminate weeds between rows. The specific equipment required consists of a cultivator and the same suspended boom sprayer of the baseline scenario for the application of the herbicide within the rows. The herbicide ingredients will correspond to the cheaper ones obtained in the previous scenario.

In the case of the conventional system, chemical control will be completely eliminated by replacing it with mechanical control. The necessary machinery consists of the same cultivator that is used in the minimum tillage scenario for weed control between rows and a vertical axis rotary implement that is able to retract when touching trees for mechanical control within the rows. Consideration of the latter scenario will also allow the economic impact of abandoning CA systems to be studied and its environmental consequences to be assessed.

Vegetal groundcovers: with this type of management, soils are protected against water erosion caused by rain. However, these covers must be controlled because they normally compete with tree crops for water and nutrients. The advantages of groundcovers can be achieved through natural or planted covers that will be mechanically controlled. Control between rows requires a brushcutter.

For the case of planted covers, in addition to a rotary brushcutter for cutting weed stems at ground level, the cost of seeds will be added. These seeds can be selected from species such as *Festuca*, *Trifolium*, *Brachipodium* or *Medicago*, and will be renewed every five years. It is also necessary to use a seed drill and a flex-tine harrow after sowing to bury the seeds. All the costs related to sowing the selected species (seeds and tillage) will be prorated over five years. Table 4 in the Annex summarizes information on tree crops scenarios, including all technical descriptions of the equipment used, the cost of machinery time and working time.

RESULTS AND DISCUSSION

Herbaceous crops

Table 5 shows the total costs of crops under the scenarios considered. The baseline scenario of direct sowing is cheaper than that of minimum tillage basically because of the lower number of hours of work required in sowing operations. This result agrees with previous studies in

Table 4 - Equipment characteristics, time cost and working time by agricultural system in tree crops

Operation	Equipment characteristic*	Time cost (€ h^{-1})	Working time ($h\ ha^{-1}$)				
			No till	Min. tillage	Conventional tillage	Natural groundcover	Planted groundcover
Various	Tractor 60 CV (30000 €)	13.27	1.71	5.14	8.00	8.57	8.76
Various	Tractor driver	11.60	1.71	5.14	8.00	8.57	8.76
Herbicide application	Suspended boom sprayer (2000 €) (6 km h^{-1}) (3 passes)	6.89	1.71	1.71	-	-	-
Inter-rows mechanical control	Cultivator 11 blades (2000 €) (4 km h^{-1}) (4 passes)	5.79	-	3.43	3.43	-	-
Intra-row mechanical control	Retractable rotary implement of vertical axis (2000 €) (3 km h^{-1}) (4 passes)	7.32	-	-	4.57	-	-
Inter-rows mechanical control	Brush cutter (3000 €) (4 km h^{-1}) (3 passes x 2 times)	6.50	-	-	-	5.14	5.14
Intra-row mechanical control	Retractable rotary brush cutter implement (2000 €) (3km h^{-1}) (3 passes)	9.76	-	-	-	3.43	3.43
Sowing groundcovers (every 5 years)	Seed drill (1700 €) (8 km h^{-1})	6.07	-	-	-	-	0.08
Sowing groundcovers	Flex-tine harrow (800 €) (6 km h^{-1})	2.11	-	-	-	-	0.11

* In brackets market price of equipment, speed and number of passes.

Table 5 - Costs of alternative scenarios in herbaceous crops

Cost (€ ha^{-1}) (machinery, labour and inputs)	Baseline scenario		Alternative herbicide (T1)		Alternative herbicide (T2)		Conventional tillage
	Min. tillage	Direct sowing	Min. tillage	Direct sowing	Min. tillage	Direct sowing	
Cost of pre-sowing herbicide ingredients	120.00	120.00	621.14	621.14	499.01	499.01	-
Cost of post-sowing herbicide ingredients	389.25	460.55	389.25	460.55	389.25	460.55	319.61
Herbicide application	54.28	54.28	54.28	54.28	54.28	54.28	31.00
Preparatory tillage	-	-	-	-	-	-	123.32
Sowing	107.48	103.84	107.48	103.84	107.48	103.84	107.48
Tractor cost	183.56	140.92	183.56	140.92	183.56	140.92	320.96
Labour cost (tractor driver)	71.92	55.20	71.92	55.20	71.92	55.20	125.76
COST OF ROTATION (€ ha^{-1})	926.49	934.79	1427.63	1435.93	1305.50	1313.80	1028.13
% w.r.t. baseline	100.00	100.00	154.00	153.60	140.90	140.54	110.97

different areas of Spain where arable crops in rainfed agriculture are important. For example, Arnal (2010) estimates a reduction of between 5 and 51% of working time with respect to the conventional system depending on the type of crop and the study area.

However, in the case of wheat, direct sowing is more expensive than minimum and conventional tillage as under this system there are often problematic weeds such as *Bromus* spp. The herbicides that control these problematic weeds are more expensive than those used in other systems where tillage facilitates their control (see Table 5). Something similar occurs with pea although in this case direct sowing is cheaper than minimum tillage. Nevertheless, crop rotation is expected to minimize weed control problems in relation to mono-cropping strategy. In addition, the inclusion of leguminous crops (pea) will enhance the natural fertility of the soil.

Replacing glyphosate with glufosinate or diquat increases costs by at least 54% and 41% respectively for both systems. It is important to underline that the calculations made are optimistic as to the efficacy of these herbicides as it is likely that additional passes and/or products will be needed to obtain weed controls as effective as those achieved by glyphosate. In addition, glufosinate is considered to have a low environmental impact, while diquat is a high-impact herbicide, so its use implies a higher environmental risk.

Although no additional passes are needed, the costs increases are greater than those obtained in the conventional tillage scenario, which represents a 10% increase over direct sowing and an 11% increase over minimum tillage. The higher machinery and labour costs of conventional tillage preparatory work would be offset by the increased price of glyphosate substitute ingredients in chemical control.

This result shows that conservation agriculture systems in cereal crops can be seriously threatened with a prohibition on the use of glyphosate, as alternative active ingredients are more expensive and/or less effective, making mechanical control (conventional tillage) the cheapest alternative.

Given that the current cereal area in Spain under the direct sowing technique is 546,859 ha, the economic cost of eliminating glyphosate would amount to 207 million euros as a result of the substitution by alternative herbicides. The costs for the area under minimum tillage would reach to 569 million euros.

Perennial crops

Table 6 shows the results obtained for tree crops. The alternative herbicide scenarios T3 and T1 are the less expensive, with an increase of 57% and 72% with respect to the baseline, while T2 is the more expensive of those considered (145% higher). Concerning the environmental effects of these alternatives, the active ingredients MCPA, fluroxypyr, glufosinate and diflufenican have a low environmental impact, amitrol has a medium impact while oxyfluorfen and flazasulfuron have a high impact. Therefore, the proposed T3 treatment is not only the cheapest alternative proposed for tree crops, but also has the least environmental effects.

On the other hand, the change to minimum tillage with superficial soil works implies an increase in costs of 60% with respect to the baseline scenario, while the change to conventional tillage is 91% more expensive. Groundcover alternatives are 112% (for natural) and 136% (for planted) more expensive.

Our analysis shows that under the glyphosate ban there are alternative chemical controls that would allow the no-till system to be maintained, although this result depends, as already indicated, on the effectiveness of weed control of alternative ingredients. If more chemical treatments are needed, the farmer may have an incentive to switch to the minimum tillage system, which is the next lowest cost option. The next preferred situation would be conventional tillage rather than groundcovers. These results indicate that without the possibility of using glyphosate, no-till and minimum tillage systems are no longer as economically attractive compared to conventional system and groundcovers, as herbicide costs increase and more extensive monitoring of weeds in the fields is likely to be required.

Table 6 - Costs of alternative scenarios in perennial tree crops

Cost (€ ha^{-1}) (machinery, labour, and inputs)	No-till (Baseline scenario)	Alternative herbicide			Min. tillage	Conventional tillage	Natural groundcover	Planted groundcover
		T1	T2	T3				
Cost of herbicide ingredients	77.76	172.87	269.57	152.81	52.40	-	-	-
Herbicide application	11.78	11.78	11.78	11.78	11.78	-	-	-
Sowing of groundcovers (seeds+machinery; annual cost renewed every 5 years)	-	-	-	-	-	-	-	26.73
Soil tillage with cultivator	-	-	-	-	19.86	19.86	-	-
Intra-rows weed control	-	-	-	-	-	33.45	33.48	33.48
Inter-rows weed control	-	-	-	-	-	-	33.41	33.41
Tractor cost	22.69	22.69	22.69	22.69	68.21	106.16	113.72	116.24
Labour cost (tractor driver)	19.84	19.84	19.84	19.84	59.62	92.80	99.41	101.62
TOTAL COST (€ ha^{-1})	132.07	227.18	323.88	207.12	211.87	252.27	280.02	311.48
% w.r.t. baseline	100.00	172.00	245.23	156.82	160.42	191.00	212.00	235.84

Considering the number of hectares of no-till in Spain and assuming that the farmer adopts a cost-minimizing behaviour, management practices based on the use of glyphosate would be replaced by other herbicide treatments (T3). Maintaining no-till and minimum tillage systems in current areas would cost 87.7 million euros due to the change in herbicides. Moving from no-till and minimum tillage to natural groundcover system, the cost would be 262 million euros and 342 million euros for planted groundcovers.

Global evaluation

Two baseline scenarios are considered for herbaceous crops: minimum tillage and direct sowing. Three alternatives are assessed: herbicide programs T1, T2 and conventional tillage. Our calculations indicate that the best alternative to the prohibition of glyphosate in herbaceous crops is to switch to conventional tillage, followed by herbicide treatments T2 and T1. This implies that CA techniques for herbaceous in rainfed agriculture could be seriously threatened with a ban on glyphosate because, although the working time required is less than in the conventional system, economic profitability is lower due to increased costs of substitute herbicides.

In the case of perennial crops, the baseline scenario is no-till and seven alternatives are evaluated: herbicide programs T1, T2, T3; minimum tillage, conventional tillage and groundcovers (natural and planted). The chemical alternative T3 and also minimum tillage would be better options than conventional tillage and would allow conservation systems to be maintained in current areas, although costs will increase by 56% (no-till) and 60% (minimum tillage) compared to the baseline scenario.

The total economic losses resulting from the elimination of glyphosate would reach 476 million euros per year in the whole country if the current area under CA systems were kept constant. But in addition to the economic costs associated with the glyphosate ban, other considerations should be made about the possible environmental costs associated with alternative herbicides and also those arising from the likely abandonment of CA farming for conventional tillage. With respect to the first issue, herbicides replacing glyphosate are less effective in controlling weeds and may require more applications and/or additional ingredients to achieve similar control, so environmental impacts must be carefully assessed. In terms of the effects of reducing or abandoning CA systems, conversion to the conventional system would lead to an increase in soil erosion, energy consumption and CO_2 emissions, as well as a likely increase in working time and farm management costs due to the lower efficiency of substitute herbicides.

According to the data available for herbaceous crops in Spain (IDAE, 2009), the average value of the energy consumed for wheat on conventional tillage represents an increase of 25% over direct sowing and 12.4% over minimum tillage, while in the case of barley the increases are 59% over direct sowing and 19.4% over minimum tillage. In addition, the average fuel consumption in conventional wheat (83.82 L ha^{-1}) is 165% higher than in direct sowing and 99% higher than minimum tillage. In barley, the average fuel consumption in conventional (78.87 L ha^{-1}) is 178% higher than direct sowing and 126% higher than minimum tillage.

In the case of tree crops, banning glyphosate for weed control would imply the use of more expensive and probably less effective alternative herbicides to maintain non-till and minimum tillage systems. The groundcover option implies agronomic and environmental advantages, as it is estimated that they have a positive effect on the CO_2 capture (IDAE, 2009), on the biodiversity and on the level of social welfare (Gómez-Limón and Barreiro, 2012), although they would imply greater complexity for the farmer and a higher economic cost.

Despite the evidence supporting CA systems, it should be remembered that the massive use of glyphosate and other chemical herbicides implies long-term threats (risk of tolerance or resistance, water pollution and possible health effects still unknown). Although glyphosate has little tendency to produce resistance compared to other active matters, more than 300 events affecting 40 species have been reported due to its extensive use (Heap, 2018). These risks and their related economic effects must be considered by farmers and policy makers in the search for more sustainable systems.

Kallas et al. (2010) suggested that the factors that determine the adoption of an agricultural system by farmers are diverse and can be classified as economic and non-economic. In the case of CA, economic factors would include obtaining long-term benefits, cost savings, input prices and public support; whereas in non-economic factors we find mainly farmer's environmental attitudes and opinions, favourable climatic conditions and also time savings and simplicity of farm management. Most studies analysing the advantages of conservation techniques have found that both types of factors are relevant (Giller et al., 2009; Kassam et al., 2012; Sanz-Cobena et al., 2017) and influence each other in complex ways. In this line, economic aspects such as high fuel prices and time savings seem to have played a key role in the rapid and widespread conversion of fields in many countries like Spain. Moreover, evidence in the literature on the environmental advantages of conservation techniques has influenced farmers' positive attitudes and opinions favouring their adoption (Gónzalez-Sánchez et al., 2010; López-Garrido et al., 2014).

Our results confirm that both economic and non-economic aspects would negatively affect the adoption of CA in the prohibition scenario.

In summary, in CA and other environmentally friendly farming systems, weed management is a key issue because the combination of measures needed to avoid the use of chemical herbicides increases the complexity of control, which could make it difficult for farmers to adopt. It is therefore crucial to assess whether the benefit incentives remain in a glyphosate ban scenario.

This study shows that the glyphosate prohibition would have a negative impact on the economic and non-economic factors of CA adoption in Spain by confirming an increase in time and labour needs and also losses in economic profitability of conservation systems. These negative effects are especially relevant for herbaceous crops as the conventional system will be more profitable than conservation system. In the case of tree crops there are some alternatives that would maintain profitability of the CA compared to conventional tillage, although farmers would assume significant economic losses. Our results suggest that additional institutional efforts should be made in order to evaluate the negative environmental effects of CA abandonment and also to promote the search for technical solutions that allow farmers to adapt to new conditions by supporting sustainable production systems in the long term.

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