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THE SIGNIF ICANCE OF HARVEST RESIDUES IN THE SUSTAINABLE MANAGEMENT OF ARABLE LAND. II. HARVEST RESIDUES MANAGEMENT

Pržulj Novo[1], Tunguz Vesna[2], Jovović Zoran[3], Velimirović Ana[3]

[1]*Faculty of Agriculture, University of Banja Luka, novo.przulj@gmail.com*
[2]*Faculty of Agriculture, University of East Sarajevo*
[3]*Biotechnical Faculty, University of Podgorica*

SUMMARY

Harvest residues (HR) are one of the important aspects of sustainable management in agriculture, representing a significant portion of organic matter (OM) that can be retained or removed from agro-ecosystems. There are several ways to manage plant residues: (i) burning, (ii) incorporation in soil, (iii) leaving plant residues after harvest on the soil surface in form of mulch, (iv) undersowing crops in HR and (v) baling and removing HR from the plot. Burning is the most unreasonable action in agricultural production, which is prohibited by legal regulations in force. The burning means a complete loss of OM - N and S are irretrievably lost in the air, mineral substances remain in ash, and microorganisms in the soil surface layer are destroyed. Incorporation of HR may be complete or partial, depending on the soil cultivation method applied.

This HR management method has a number of soil benefits: increases content of nutrients, OM and humus; increases microbiological activity; improves soil water, air and physical properties; improves soil structure, ultimately contributing to the increase in soil fertility and plant growth. Two practical approaches that were once common, have been neglected. Namely, undersowing and mixed cultivation where various species are simultaneously grown with or between plantings of a main crop. Removal of HR indirectly leads to a decrease of the organic matter in the soil. In essence, there is a need to determine the size of acceptors and the return rates of organic residues of different quality, and to increase the efficiency of nutrient cycling from residues through various land acceptors and crops, with minimal losses from the system.

Keywords: *harvest residues, incorporation of harvest residues, soil quality, soil organic matter*

INTRODUCTION

Increasied attention is paid worldwide to the development and application of biofuels, produced from renewable primary and secondary agricultural raw materials and the application of circular economy. There is a special interest in the use of above ground vegetative mass from primary plant production (e.g. small grain straw, soybeans, oilseeds) for the production of industrial fibres or biofuels [1,2,3,4,5]. One-sided definition of using harvest residues (HR) and their removal from agricultural arable land generates very harmful consequences to land quality [7,8]. Above and underground residues have a special role in maintaining the preferable content of organic carbon (C), microbiological and physical soil properties and realization of the genetic potential of crops [9,10,11,1213,14].

Awareness and knowledge that HR are a huge natural resource, and not waste, has been developed to a great extent. There are significant amounts of nutrients in HR that can be returned to the soil every year after harvest [15]. The ability of leguminous plants to perform biological nitrogen fixation (BNF) and to recycle fixed nitrogen (N) when legume residues are in the soil can be a significant source of organic N in the soil, as well as a source of N for the next crop [16]. The global amount of N recycled in agricultural crop land via HR can be 25–100 million tons per year [17]. Essentially, there is a need to determine acceptor sizes and return rates of organic residues of different quality, and to increase the efficiency of nutrient cycling from residues through different soil acceptors and crops, with minimal losses from the system (5,12,].

This may include the development of practices to improve nutrient immobilization when cultivated plants are not grown on the soil, as well as practices to increase nutrient availability when cultivated plants are present. In order to determine the actual amount of plant residues necessary to maintain soil productivity and ensure environmental protection through minimal losses of nutrients and soil erosion, data on kinetic decompositions of HR and mineralization-immobilization rate of HR of different quality (leguminous and non-leguminous) plants are necessary [18]. Adding organic matter (OM) to soil through restoring HR also improves soil structure, affects soil water, air and temperature relationships, helps control waterlogging and erosion, and facilitates soil cultivation. The aim of this work is to analyse the negative consequences of removing HR from arable land and the positive effects of their return to the soil. The paper presents various ways of HR management.

MANAGEMENT OF HARVEST RESIDUES

The management of plant agricultural residues and soil organic matter (SOM) and their relationship with soil cultivation and crop rotation is of particular importance for maintaining soil quality and achieving the favourable yield of cultivated plants. In search of an answer to this question [19] investigated the effect of conventional plowing and shallow reduced tillage in barley-vetch and barley-vetch-wheat-vetch crop rotations with different variants of straw use (incineration, removal, plowing) and addition of 10 t ha^{-1} of compost every second and fourth year with the aim of determining the distribution of OM in the soil layer of 0–30 cm, total organic and labile N and microbial C and N. With reduced tillage, there was an increase in OM in the soil at a depth of 0–20 cm for all three variants of straw use amounting 2.7 g kg^{-1} on average.

Adding compost every other year, instead of burning or removing HR, significantly increased total organic N in the 0–20 cm soil profile (by 0.22 g kg^{-1}), doubled labile N and C in the 0–5 cm depth, and increased the ratio of labile N to total N by 4% in the 0–20 cm profile. Therefore, by choosing an appropriate method of arable land management, the content of labile OM in the soil can be quickly increased, but it is also quickly used up. Shallow cultivation of the soil with the addition of compost contributes to the increase of the OM content in the soil, and thus the quality of the soil. In conditions of intensive plant production, where HR is not removed from arable land, the mentioned system represents an improvement in the agriculture of arid areas.

There are several ways of HR management available to farmers: (a) burning, (b) incorporation into the soil, (c) leaving after harvest on the soil surface - mulch, (g) sowing of cultivated plants in HR (undersowing crops), and (d) baling and removal of HR cultivated plants from the plot.

Burning of crop residues

Burning of HR (Figure 1a) is the most unreasonable action in agricultural production, which is prohibited according to existing legal regulations. Burning means a complete loss of OM - N and S go irreversibly into the air, mineral substances remain in the ash, and microorganisms in the surface layer of the soil are destroyed [20]. Microorganisms play a major role in soil formation and ecology, because as "natural soil engineers" they regulate the flow of nutrients to plants and assist in N fixation, ultimately promoting the detoxification of natural inorganic and organic pollutants in the soil. It is estimated that one gram of soil contains: 10^{8-9} bacteria, 10^{5-8} actinomycetes, 10^{5-6} fungi, 10^{3-6} microalgae, 10^{3-5} protozoa,

10^{1-2} nematodes, 10^{3-5} other invertebrates - there are more organisms per gram of land than there have been human beings on Earth to date [21,22]. In this way, complete destruction of weed seeds is not achieved. Partial justification for incineration of HR is only in the case of a stronger attack of plant diseases transmitted by HR.

Incorporation of crop residues into the soil

Incorporation of HR (Figure 1b) can be complete or partial, depending on the applied soil cultivation methods. This HR management method has a number of advantages for the soil: increasing the content of nutrients, OM and humus and microbiological activity; improvement of water-air and physical properties; improving the structure; ultimately contributing to the increase of soil fertility and the yield of cultivated plants. Plant residues are plowed by peeling the surface layer of the soil to a depth of 10-15 cm, which are then decomposed under the influence of microorganisms. This is a favourable period because after the harvest the soil still contains certain amounts of water, which enables the good performance of this operation and suitable development of the processes that follow. Violation of capillarity by peeling prevents evaporation, which contributes to maintaining moisture in the soil. In addition, this enables better absorption and retention of water in the soil, provokes the germination of weed seeds that are later destroyed, activates microbiological processes and brings the soil to a state of biological maturity [23]. By stimulating the biological activity of the soil, the structure, water, air and thermal properties of the soil are positively affected.

Figgure 1. Harvest residue

(a) burning, (b) incorporating into the soil, (c) leaving after harvest on the soil surface – mulch, (d) baling and removal

The decomposition of HR is carried out by the action of two processes: (1) decomposition to water, carbon dioxide, ammonia and mineral substances that can be used by the next crop and (2) transformation into humus [24]. SOM is mostly found in the rhizosphere, where the microbiological activity is highest. OM mainly consists of three parts: (1) the living part (microorganisms, fauna, and roots), (2) the remains of dead organisms in various stages of decomposition, and (3) humus. If OM is partially decomposed, effective humus is created and plants can use it immediately. In the process of complete humification, a stable humus is formed, which is more difficult for microorganisms to break down. The value of HR depends on the nutrient content, the C/N ratio and the amount of cellulose and lignin. The C/N ratio is highest in straw of small grains 50–150:1; wheat 75:1, maize 50–60:1, sunflower 40–50:1, and lowest in alfalfa 14:1 [25]. This ratio in mature manure is 20:1, and in permanent humus about 10:1. When incorporating organic matter with a low N content, 0.40–0.50%, and a large proportion of cellulose, hemicellulose, lignin, and other carbohydrates, intense microbiological activity develops, which leads to "nitrogen depression" due to the reduction of nitrate N in the soil and its incorporation into microorganisms. Microorganisms use nitrate N from the soil solution for their development, and thus symptoms of N deficiency appear on the crop during the growing season [26]. A lack of other nutrients can also occur, but it is of such magnitude that it can be ignored. Small grains are the most sensitive crops to nitrogen depression, row crops are less sensitive, while leguminous plants are insensitive. In the era of energy crisis, HR are a valuable product because they contain a large amount of energy (necessary for microorganisms) that should be used on the plot by plowing, and not by removing it from the plot. Nutrients in HR are found at the point of application, no transport is necessary, and they have the same nutritional value as manure. Depending on the plant species, plowing HR provides 20-25% N, 25-50% P and 30-80% K for the next crop [27].

To eliminate nitrogen depression, in addition to regular N fertilization, it is recommended to add 7–8 kg of N per 1 t of dry plant mass. This amount of N ensures the unhindered decomposition of plant residues and eliminates the deficiency of N in the next crop, thus avoiding the occurrence of nitrogen depression. When plowing the tap roots and leaves of sugar beet and roots and above-ground remains of leguminous plants, no additional amounts of N are needed, because the C/N ratio in those plants is low; for example, in the leaves and tap roots of sugar beet is about 10:1, and in leguminous plants is about 15:1, which is lower than in mature manure [28]. In addition, the root remainings of leguminous plants are evenly distributed in the soil in vertical and horizontal directions. The time of plowing depends on the time of harvest, although plant residues can remain longer in the field, because they partially soften and are easier to plow. After early crops, such as winter small grains, plant residues are plowed with peeling, and for late crops, such as maize, residues are incorporated in the fall with basic tillage. Plowing plant residues in the spring is unfavourable. The depth of plowing depends on the amount of organic mass that needs to be plowed. The straw of small grains and soybeans and similar plant residues can be plowed up to a depth of 20 cm, and for plowing maize, due to its greater mass, a higher depth is required, usually 25–30 cm. HR on soils of good biogenicity decompose quickly, thus increasing the microbial population and mesofauna [29]. Part of the partially decomposed OM rebuilds humus (≈20–30%) with the help of microorganisms, and this process is called humification. Biogenic elements in HR, manure or humus, after mineralization, with the help of microorganisms, pass into mineral forms that plants can adopt again [25].

In a multi-year stationary field experiment, which was carried out as part of a series of experiments by the International Commission for the Study of Soil Fertility on the experimental field of the Institute of Agriculture and Vegetables in Novi Sad in a three-field experiment; maize-soybean-wheat, with the application of 5 tons of maize straw (with the addition of 50 kg N per ha to prevent nitrogen depression), a significant effect of straw input on wheat grain yield was obtained (Table 1) [30]. In the examined three-year period, the average grain yield on variants without straw plowing was 4.34 t ha^{-1}, and on variants with straw plowing it was 7% higher, i.e. 4.46 t ha^{-1}.

Table 1. Grain yield (t ha^{-1}) at different N-rates and straw management [30]

Fertilization variant		Variety			Average fertilization (t ha^{-1})
Straw	N quantity (kg ha^{-1})	Pobeda	Sofija	Sremica	
With straw	Ø	3,64	3,12	3,41	3,39
	0	3,90**	3,36**	3,76**	3,67**
	90	5,34**	4,61**	5,19**	5,05**
	150	5,71**	5,66**	5,81**	5,73**
	Average	4,65**	4,19**	4,54**	**4,46****
Without straw	0	3,16	2,76	3,37	3,10
	90	4,54	4,40	4,82	4,59
	150	5,00	4,42	5,18	4,87
	Average	4,23	3,86	4,46	4,18
Variety average (t ha^{-1})		4,47	4,05	4,51	**4,34**

The highest yield on average for all three tested varieties (5.73 t ha^{-1}) was obtained when fertilizing with 150 kg ha^{-1} of N in the treatment with long-term plowing of straw. The grain yield of this variant was significantly higher compared to other variants on which straw was plowed, as well as compared to all variants without straw application. In the variant with 90 kg N ha^{-1} + straw, a significantly higher yield (5.05 t ha^{-1}) was obtained compared to other variants, as well, with the exception of the variant with 150 kg N ha^{-1} without straw plowing. The highest grain yield on the variants on which straw was not plowed was obtained when fertilizing with 150 kg N ha^{-1} (4.87 t ha^{-1}), and was significantly higher compared to 0 and 90 kg of applied N per hectare [30].

Varieties Pobeda and Sremica achieved statistically similar grain yields, both on variants with straw plowing (4.65 and 4.54 t ha^{-1}, respectively) and without straw application (4.23 and 4.46 t ha^{-1}). In both cases their yield was significantly higher compared to the Sofia variety (4.19 t ha^{-1} and 3.86 t ha^{-1}, respectively). The effect of long-term plowing of straw on the yield of wheat grains in comparable test varieties is shown in Table 2, and it ranged depending on the variety and the amount of applied N within the limits of only 210 kg of grain (for the Sofia variety at 90 kg N ha^{-1}) to highly significant 1,240 kg ha^{-1} (for the same variety when fertilized with 150 kg N ha^{-1}). Observed on average for all three varieties; in the control variant (without N application), long-term straw plowing increased grain yield by 570 kg ha^{-1} (18.4%); on the variant with 90 kg of N by 460 kg (10%), while on the variant with the most intensive fertilization (150 kg N ha^{-1}), straw plowing gave the absolute highest yield increase of 860 kg ha^{-1}, i.e. 17.7%. The average yield increase in the experiment achieved by straw plowing (average for all three varieties and applied amounts of N) was 640 kg of grain, i.e. 15.3%, and by variety it was 750 kg (Pobeda), 680 (Sofia) and 460 kg ha^{-1} (Sremica). Thus Pobeda variety had strongest reaction to straw plowing, while the effect on the Sremica variety was the weakest, Table 2, [30].

Table 2. The effect of straw management on grain yield (t ha^{-1}) [30]

Nitrogen dosage	Straw	Variety			Average
		Pobeda	Sofija	Sremica	
0 kg N ha^{-1}	With straw plowing	3,90	3,36	3,76	3,67
	Without straw plowing	3,16	2,76	3,37	3,10
	Difference:	0,74**	0,60**	0,39**	0,57**
90 kg N ha^{-1}	With straw plowing	5,34	4,61	5,19	5,05
	Without straw plowing	4,54	4,40	4,82	4,59
	Difference:	0,80**	0,21**	0,37**	0,46**
150 kg N ha^{-1}	With straw plowing	5,71	5,66	5,81	5,73
	Without straw plowing	5,00	4,42	5,18	4,87
	Difference:	0,71**	1,24**	0,63**	0,86**
Average for all N dosages	With straw plowing	4,98	4,54	4,92	4,82
	Without straw plowing	4,23	3,86	4,46	4,18
	Difference:	0,75**	0,68**	0,46**	0,64**

[31] report a positive impact of plowing HR of maize previous crops on the yield of soybeans, variety Valjevka (Tab. 3). With basic soil preparation for maize, 80 kg ha^{-1} of P_2O_5 and K_2O and 100 kg ha^{-1} of nitrogen fertilizer KAN (27% N) were applied, and in the spring with pre-sowing preparation of 100 kg ha^{-1} 27% KAN. Apart from NS Nitragin preparation for soybean seed inoculation, no fertilizers were used during soybean cultivation. The increase in the yield of soybeans under the influence of plowing HR previous crop in the five-year period amounted to 10.43%, and it varied from 7.03% in 2014 to 15.94% in 2015 (Table 3).

Table 3. Soybean grain yield (kg ha^{-1}) at different straw management (HR) [31]

Year	Without HR	With HR	Average	Yield increase (%)
2012	1.975	2.240**	2.108	13,4
2013	2.831	3.182**	3.007	12,4
2014	4.478	4.793**	4.636	7,0
2015	2.862	3.318**	3.090	15,9
2016	4.558	4.913**	4.736	7,8
Average	3.341	3.689**	3.516	10,4

Other authors also report a positive effect of HR plowing or manure application on the yield of cultivated plants [30,32,33,34,35], increased total N and C content, improved soil fertility or reduced N leaching [36, 37, 38]. The application of nitrogen fertilizers with plowed above-ground biomass significantly increases the amount of plant residues produced, that, along with incorporation into the soil increases the humus content and the efficiency of C retention in the soil [39,40]. Lower molecular compounds resulting from the decomposition of HR, plants can directly adopt and use in the circulation of matter and energy, and some substances can stimulate their growth and development [41].

In maize monoculture on chernozem (Novi Sad, Serbia), the long-term application of mineral fertilizer (32 years) did not affect the increase in the content of soil organic carbon (SOC), i.e. OM, compared to the treatment without fertilization [27]. Conversely, HR plowing or manure fertilization increased SOM concentration and reserves. At the Zemun Polje location, the results of long-term field trials, which were set up in 1971, show that the SOM content increased significantly with the application of manure and plowing HR. The applied OM also had a positive effect on SOC concentration and reserves compared to the treatment fertilized only with mineral fertilizers [42].

Leaving plant residues after harvest on the soil surface

Without burning or any method of incorporation of HR into the soil and direct seeding through HR is feasible when lower amount of HR is present. A large amount of HR remaining on the surface often leads to machine failure, which affects the precise sowing of subsequent crops [43].

Undersowing crops

In today's agricultural environment, the conservation of water, soil, and energy is of utmost importance. Two practical approaches that were once common, have been neglected. Namely, undersowing and mixed cultivation, where various species are simultaneously grown with or between plantings of the main crop. White clover and alfaalfa have proven to be suitable for undersowing in Moldova where undersowing of these legumes significantly reduced weediness [44]. Camelina (*Camelina sativa*) effectively inhibits weeds, so herbicide treatments are not necessary [45].

Baling and removal of crop residues after harvest

The removal of HR indirectly leads to the reduction of organic matter in the soil. Surplus of straw from agriculture (especially of poor quality) can be used for a variety of purposes, such as feed, fuel, building material, bedding for livestock, composting for growing mushrooms, substrate for strawberries, cucumbers, melons and other crops, mulching for orchards and raw material for production [46,47].

CONCLUSION

The development of effective harvest residue management systems depends on a thorough understanding of the factors that control residue decomposition and their careful application within a specific crop production system. No harvest residue management system is superior in all conditions. For this reason, farmers have a responsibility in making management decisions that will allow them to optimize the yields of cultivated plants and minimize negative impacts on the environment. Taking into account all factors, multidisciplinary and joint research should propose the best crop residue management system for each specific case, in order to improve agricultural productivity and sustainability and reduce the negative impact on the environment.

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