EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2023, 24(3), 241–248
https://doi.org/10.12912/27197050/159433
ISSN 2719–7050, License CC-BY 4.0

Received: 2022.12.30
Accepted: 2023.01.27
Published: 2023.02.25

Evaluation of the Impact of No-Till on Soil Erosion Using Soil Aggregate Stability and Fallout Radionuclides in Northern Morocco

Hamza Iaaich[1,2*], Rachid Moussadek[1,3], Rachid Mrabet[1], Ahmed Douaik[1], Bouamar Baghdad[4], Moncef Benmansour[5], Anis Zouagui[5], Nezha Asserar[2], Abdelhak Bouabdli[2]

[1] National Institute of Agricultural Research, PO Box 415, RP, Rabat, Morocco
[2] Ibn Tofail University, Faculty of Sciences, University Campus, PO Box 133, Kenitra, Morocco
[3] International Center for Agricultural Research in Dry Areas, Av. Hafiane Cherkaoui, Rabat, Marocco
[4] Hassan II Institute of Agronomy and Veterinary Medicine, PO Box 6202, Rabat Instituts, Rabat, Morocco
[5] National Center on Energy and Nuclear Science and Techniques, PO Box 1382, Maamora Road, Salé, Morocco
* Corresponding author's e-mail: hamza.iaaich@inra.ma

ABSTRACT

The aim of this work is to assess the impact of no-till based cropping system on soil erosion using two indicators. The experiment plot was under no-tillage (NT) for four years, adjacent to a plot under conventional tillage (CT) with same other management practices. The two used indicators are Le Bissonnais soil aggregates' stability test and the activities of the fallout radionuclides (FRN) ^{7}Be and ^{137}Cs. For each radionuclide, the reference sites were identified and sampled using grid sampling approach and the study sites (the two plots) were sampled by applying a one-dimensional point transect sampling. Five samples were collected from each study site with 10m increment. The results showed that the mean weighted diameter (MWD) was of 2.2 for the NT plot and 2.0 for the CT plot, this indicates a lower soil detachability under the no-till system. For the FRN results, the ^{7}Be activity showed that the NT plot retained 79% of the reference site activity and the CT plot retained 54%. The ^{137}Cs activity tests showed also that the NT plot retained more of reference site activity. The mass balance conversion models application to the FRN results showed that the no-till system generated 10% less soil erosion rate than the conventional tillage. The results showed that in spite of needing more than 4 years implementation for statistical significance, no-till helps reducing water erosion in the hilly agricultural lands of Northern Morocco.

Keywords: soil erosion; no-till; aggregate stability; fallout radionuclides; Morocco.

INTRODUCTION

Water erosion is a major challenge for agricultural lands in the Mediterranean basin [1] and specifically in Morocco [2,3], with the highest soil loss rates reported in the Northern part of the country [4, 5]. In fact, Moroccan soils are not organogenic, they are generally of poor to medium organic matter contents and thus present a loose aggregate stability and a low resistance to water erosion. Added to the pedogenetic factors, one can owe the soil fragility in a large part of the Moroccan agricultural lands to the dominant agricultural management systems which are within degrading processes, in both smallholder and modern agriculture models [6, 7]. In this sense, the Moroccan case is similar to other ones of vulnerable environments in Africa [8], South-East Asia [9, 10] and Latin America [11]. At a global scale, tillage, being an anthropogenic perturbation, stands as one of the four energy sources for soil erosion [12]. As an alternative to the intensive tillage-based cropping systems, the no-till system, a pillar of conservation agriculture, is reported to have benefic impact on soil physical properties, such as soil organic matter content and aggregates' stability, retrieving levels that could lower soils' erodibility and prevent their vulnerability to various hazards. In Morocco, several studies showed the impact of medium-term and long-term no-till based systems on soil physics in the agricultural lands, especially in the semi-arid and arid areas. In fact, a ten years no-till based cropping plot in rainfed Central Morocco accumulated more organic matter at the soil surface layer and enhanced its aggregate stability in comparison with a conventional tilled neighboring plot [7]. Similar results were found with a better behavior of the soil in the case of intensive cropping compared to wheat-fallow based system [13]. As per the residue component, a study in Central Morocco reported that significant soil sediment loss was observed starting from 50% mulch when coupled to no-till, for a 6 years no-till plot on a Mediterranean vertisol of the Zaer zone [14]. At long term retrospective scale, a research work retrieving results from up to 30 years no-till based system trials, reported a continuous organic matter accumulation at the root zone layer, along with other various soil quality that are related to erodibility [15]. Also, at long term prospective scale, several modeling studies show positive impact of no-till based systems on soil physics and vulnerability to water erosion in the Moroccan context [16] and in the similar North African environment of Tunisia [17].

Soil aggregate stability remains a key physical parameter when it comes to assess the impact of physical and biological anti-erosive measures on the soil vulnerability to water erosion. The aggregate stability of the soil reflects its ability to conserve the particles' arrangement during a splash or humectation event [18]. The same authors state that a low structural stability acts in favor of particle detachment. Thus, this physical parameter reflects the soil aggregates behavior under different erosive events. Several studies show the role of soil aggregate stability in assessing its erodibility. A study on the effect of different vegetation restoration measures in the Chinese Loess plateau, reported that the trend of the soil's aggregate stability was parallel to its ability to resist erosion, along with other soil quality parameters like soil organic carbon [19]. Same insights were reported regarding afforestation effect on soil quality under two plantations, where the increased aggregate stability occurred with decreased erodibility and vice versa [20]. Other studies were concerned by this relationship in different pedo-landscapes like Southern Spain [21], Northwest Iran [22] and Turkey [23].

As important soil erosion indicators come the fallout radionuclides (FRN) inventories and fluxes. In fact, three FRN are used to trace soil erosion and accumulation: ^{137}Cs, ^{7}Be and $^{210}Pb_{ex}$ [24–26]. These FRN have half-lifes ranging from 53 days for ^{7}Be to 30 years for ^{137}Cs, allowing soil erosion and accumulation assessment with return periods ranging from recent rainfall events using ^{7}Be to several decades using ^{137}Cs. The use of FRNs based techniques for soil erosion quantification is reported in several research works. He and Walling [27] quantified soil erosion through FRN distribution in cultivated and uncultivated soils. Gaspar and Navas [28] used ^{137}Cs for soil erosion assessment in several Mediterranean soil types under various cropping systems. In Morocco, several results show the effectiveness of FRN based techniques in assessing soil erosion at short, medium and long terms. In Central Morocco, Benmansour et al [29] showed correlation between FRN based results and the RUSLE model on a Mediterranean vertisol. Nouira et al [30] used the ^{137}Cs technique to quantify medium-term soil loss rate in a representative agricultural field of the Oued El Maleh zone (Northwest Morocco). Meliho et al [31] used the same technique in the High Atlas Moroccan Mountains, with scenarios including soil properties (organic carbon), environment (slope gradient) and land use and management.

Our study is the first that highlights the effect of no-till in mid-slope hilly environments of Northwest Morocco. Available studies on no-till in Morocco are so far focused on plains and plateaus of Central Morocco, with different landscapes and rainfall erosivity. Also, this study is one of the first to apply FRN based techniques in assessing the effect of no-till system in Morocco. These techniques are in fact sporadically used in Morocco, and this study aimed to show their effectiveness for the Moroccan crop lands, especially when comparing them to the more widely used aggregate stability parameter.

MATERIALS AND METHODS

Study area

Our research work concerned a mid-slop Vertic Regosol (WRBSR classification, FAO [32]) using soil aggregate stability and two FRN (^{137}Cs

and ^{7}Be) on two neighboring plots, one under no-till tillage and the other under conventional tillage. The experimentation plot is located in the Dar Chaoui village, at 25 km West of the city of Tetouan, North-West Morocco, with GPS coordinates 5°39'57''W and 35°35'20''N (Figure 1). The landscape is dominated by undulating environment, where major soil types are Vertic Regosols and Vertisols.The study area is of Mediterranean sub-humid climate, mean annual temperature of 17°C and a average annual precipitation 500 mm. The no-till experiment plot is of one-hectare and was under no-till for four years, with cereals-legumes rotation cropping system.

Experimental design and soil sampling

The effect of four years no-till was tested as a comparison between no-till (NT) and conventional tillage (CT) adjacent plots of one hectare, using two methods: (i) soil aggregate stability [33] and (ii) the flux of two FRN (^{137}Cs and ^{7}Be). Prior to the NT system implementation, the two plots were a part of single whole land and thus were subject to identical agricultural management.

Data analysis

Concerning the aggregates' stability test, three undisturbed soil samples were taken from the two plots, then these three stability tests were conducted for the 2–5 mm soil fraction: (i) rapid humectation test, which simulates an intense rain event, (ii) slow rehumectation test, which indicates the particles' behavior in moderate rain event after a dry period, (iii) disaggregation test in which the overall soil particle cohesion is tested. Seven aggregate fractions were then differentiated through dry sieving (>2 mm, 1–2 mm, 0.5–1 mm, 0.2–0.5 mm, 0.1–0.2 mm, 0.05 mm, <0.05 mm). The Mean Weighted Average (MWD) was calculated based on the aggregate weights in each sieve, using the equation below [33]:

$$\begin{gathered}MWD = [3.5\times(\% >2\text{ mm}) + \\ + 1.5\times(\%\ 1\text{ to }2\text{ mm}) + \\ + 0.75\times(\%\ 0.5\text{ to }1\text{ mm}) + \\ + 0.35\times(\%\ 0.2\text{ to }0.5\text{ mm}) + \\ + 0.15\times(\%\ 0.1\text{ to }0.2\text{ mm}) + \\ + 0.075\times(\%\ 0.05\text{ to }0.1\text{ mm}) + \\ + 0.025\times(\% <0.05\text{ mm})]/100\end{gathered}$$

High MWD values indicate a good aggregate stability. The ^{137}Cs and ^{7}Be activities of the two plots were compared to their activities in the reference sites. The reference site for the ^{137}Cs is a neighboring forest and that of ^{7}Be is a neighboring long-time fallow. Nine grid samples were taken from each reference site to 1m depth for ^{137}Cs and to 40 cm depth for ^{7}Be. These are the maximum depths that are reached by these two FRNs. For the study sites, five samples were taken on a transect with 10 m increment. The FRN activities were measured using Gamma High

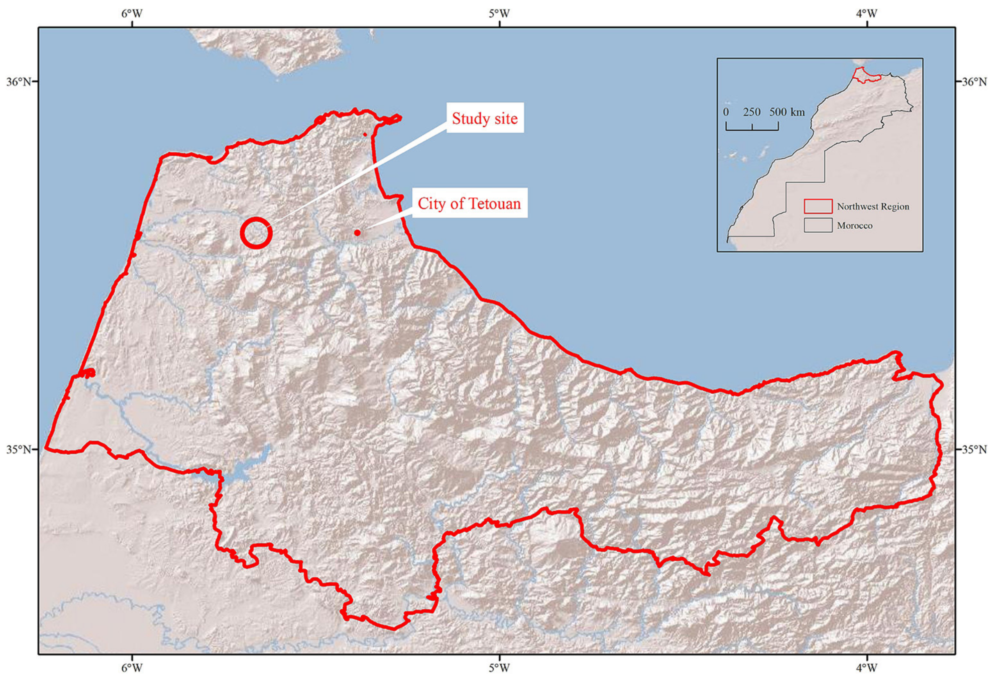

Figure 1. Location map of the study area and study site

Pure Germnium spectrometry. Finally, the Mass Balance Model II (MBM II) conversion model [34] was applied for the ^{137}Cs activities to convert them to medium-term (30 years) mean annual soil loss rates. The MBM II model comes as a complement component of MS Excel, where the inputs include the FRN activities in the reference and study sites, added to a set of parameters of the soil and crop management. Table 1 shows the parameters used for the MBM II for the ^{137}Cs activities medium-term conversion.

Student's t test using the SPSS (Statistical Package for the Social Sciences) software was applied to statistically compare the MDW and the FRNs results.

RESULTS

The calculated MDW results for the two plots are shown on Table 2 and Figure 2. The FRN results are shown in Table 3. The average MWD of the three aggregate stability tests is of 2.2 mm for the NT plot and 2 mm for the CT plot. The FRN activities show a similar pattern, ^{7}Be activities indicate that for the short term, the NT plot retained 79% of the reference site activity and the CT plot retained 54%. For the medium-term, the ^{137}Cs activities indicate that the NT plot retained 22% of the reference site activity and the CT plot retained 17%. The mass balance II conversion model applied to ^{137}Cs showed that, in a medium-term retrospective, both plots have generated erosion, with the NT plot generating 10% less soil loss rate compared to the CT plot.

For the three aggregate stability tests, the Student's t test showed no significance difference of the mean MDW between the two plots. A first data check show that the low t-value, leading to high difference probabilities, is due to the higher difference in the "within" component compared to that in the "between" component. The mean FRN activities and soil loss ratios (Table 3) show same t-value and p-value tendencies and same non significance between NT and CT plots. As detailed in the discussion section, the non-significance is likely due to, among others reasons, on one hand the recent implementation of the no till system

Table 1. Plot parameters for the application of the MBM II conversion model

Year of tillage commencement	Soil bulk density (kg·m^{-3})	Proportion factor	Plough depth (kg·m^{-2})	Relaxation depth
1954	1390	0.6	167	4

Table 2. Soil fraction percentages and MDW of the three aggregate stability tests for the two plots

Plot	Test	Repetition	> 2 mm (%)	1–2 mm (%)	0.5–1 mm (%)	0.2–0.5 mm (%)	0.1–0.2 mm (%)	0.05–0.1 mm (%)	<0.05 mm (%)	MDW
CT	Rapid humectation	1	21.39	20.91	18.46	17.38	9.71	6.41	1.26	1.28
		2	6.36	25.70	25.17	24.69	10.60	4.57	0.88	0.90
		3	14.07	30.25	22.79	18.97	7.37	3.30	0.70	1.20
	Slow rehumectation	1	94.59	3.52	1.67	0.71	0.20	0.00	0.00	3.38
		2	60.17	28.38	7.67	3.25	0.72	0.47	0.07	2.60
		3	87.32	8.79	2.89	1.49	0.39	0.19	0.11	3.22
	Disaggregation	1	28.98	31.46	18.63	11.69	4.10	2.16	0.61	1.67
		2	22.38	37.21	21.80	11.72	3.35	1.52	0.41	1.55
		3	54.16	23.82	11.08	6.59	1.81	0.85	0.24	2.36
NT	Rapid humectation	1	12.98	25.82	23.42	23.38	8.86	3.45	0.44	1.11
		2	38.62	22.80	14.67	12.28	5.36	2.77	0.56	1.86
		3	26.73	20.40	17.78	16.42	9.20	5.55	1.63	1.45
	Slow rehumectation	1	86.27	11.15	4.88	2.51	0.69	0.35	0.14	3.23
		2	60.32	22.74	11.54	5.99	1.33	0.49	0.15	2.56
		3	97.78	5.58	1.50	0.62	0.16	0.00	0.00	3.52
	Disaggregation	1	36.67	28.31	19.91	10.29	2.34	0.91	0.19	1.90
		2	46.02	26.92	14.91	8.19	2.21	0.98	0.21	2.16
		3	34.90	24.76	19.78	12.59	4.12	1.95	0.52	1.79

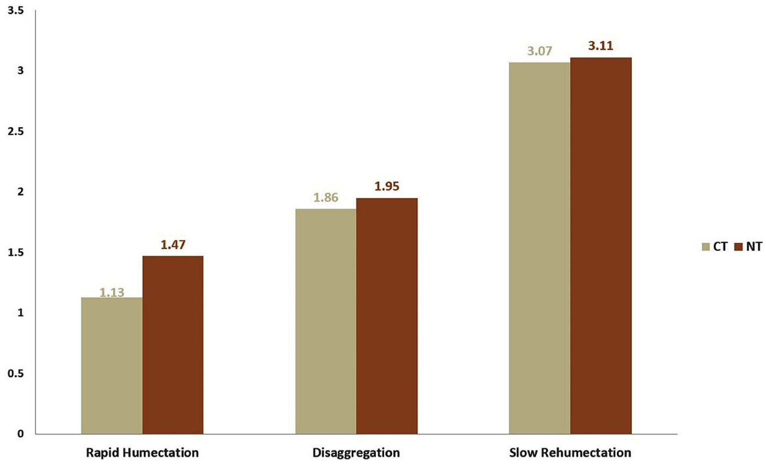

Figure 2. Soil aggregate stability test results

at the time of the soil sampling, and on another hand the intrinsic variability of the two plots' micro-reliefs due to the soil vertic characteristics and the slope gradient. The effect of some vertic characteristics such as the gilgai environment is particularly reflected in the variability of the FRN activities through the sampling transects, where a higher value at a point in comparison to the precedent one indicates a soil accumulation at that point, though the process in the whole plot is towards soil erosion in comparison with the FRN activities in the reference sites.

DISCUSSION

Soil aggregate stability

The aggregate stability results indicate a tendency towards a higher MDW for the NT plot, though statistically non-significant. The rapid humectation test shows the largest difference between NT and CT plots, followed by the disaggregation test. This reflects a better soil aggregate behavior in the case of intense rain events and better particle cohesion. The non-significance is likely due to the recent NT system implementation (4 years) at the time of the sampling and to the slope gradient that tends to overshadow the management in favor of soil particle detachment and transportation, especially in the first seasons. The NT system is known to require a number of seasons for maturation, especially under semiarid to sub-humid climate, in order to improve soil physical parameters affecting soil erosion. In the Moroccan context, a multi-date study covering three NT system sites with different implementation years in Central Morocco, showed that a significant improvement of soil organic matter was noted on the 11 years NT plot for the 0–10 cm upper soil horizon, while the 32 years NT plot showed a significant improvement of soil organic matter up to 40 cm depth [15]. On a global level, Mondal et al [35] realized a meta-analysis on the effect of NT system on soil physics at different terms and under different environments. The meta-analysis showed that long term (16 to 20 years) NT plots showed significant modifications in soil basic physical parameters like aggregate stability. The analysis also showed a lack of consensus in

Table 3. Activities of 7Be and 137Cs and the MBM II model medium-term soil loss results for the two plots

Sample	^{7}Be activity (Bq/m²)		^{137}Cs activity (Bq/m²)		MBM II ^{137}Cs conversion (t/ha.y)	
	CT	NT	CT	NT	CT	NT
1	133	237	183	233	-54	-48
2	193	280	192	246	-53	-46
3	114	170	101	156	-71	-59
4	127	182	120	95	-66	-73
5	168	203	839	1100	-16	-9
Avg.	147[a]	214[a]	287[b]	366[b]	-52[c]	-47[c]
Reference inventories : ^{7}Be : 272 Bq/m² ; ^{137}Cs : 1661 Bq/m²						

the literature when it comes to defining a reference time basis for the significant improvement of these parameters. Finally, a key message from the meta-analysis was that depending on climate and environment, MDW change under NT reaches equilibrium within certain duration, with the most rapid changes occurring under temperate, sub-tropical and tropical climate. This supports the hypothesis of an on-going maturing NT system in our study site that is located under a Mediterranean climate. In another angle, with more focus on the MDW results, the non-significance can be also owed to the soil type (Vertic Regosol). In fact, the soil vertic properties result in an intrinsic high aggregate stability (shown through a relatively high average MDW for the CT plot), especially for the slow rehumectation and disaggregation tests. For the rapid humectation test, the MDW (1.13) is the component that, added to slope gradient, goes in favor of soil aggregate stability decrease in the case of intense erosive rain event.

Yet non-significant, the MDW results remain indicative of an evolution towards the enhancement of the soil physical quality under NT system based cropping. Our results are similar to those found by authors in Morocco [7, 13] with a tendency to a higher MDW for the slow humectation test in the case of flat environments of Central Morocco, in comparison to our slightly hilly study site. With the studies on no-tillage and conservation agriculture in Morocco being more focused on plains and plateaus, the results of our study states NT based cropping system as a buffer also facing rain events in a higher slope gradient, which happen to be more erosive and occur more in the last autumn/winter seasons in Morocco.

Fallout radionucleides activity

Parallel to the MDW, the FRN results also show a better soil behavior of the NT plot, through higher activities at the study site for both ^{7}Be and ^{137}Cs and a lower soil loss rate at medium-term, though the difference is non-significant for likely the same reason as for MDW. The difference between the two plots was larger for the case of ^{7}Be, this shows a better reaction to rain events occurring within 53 days prior to the sampling date. The lower difference for the case of ^{137}Cs is, as for the MDW, due to the recent implementation of NT at the time of sampling, ^{137}Cs being a medium-term soil erosion tracer with a half-life of 30 years. Nevertheless, the difference between the NT and CT plots remains an indicator of the effectiveness of the NT based system, if we take into account, added to the recent implementation, the slow evolution of the soils in the context of semiarid to sub-humid environments of the Moroccan pedoclimate, especially in mid-slope cropping lands of the hilly environment of Northwest Morocco. In fact, in a similar way to that of soil aggregate stability, the non-significant difference between the medium-term soil loss rates under CT and NT can be owed to the initial soil loss rate in the study area, which in this case is more likely rooted in the slope gradient and rain erosivity than in the soil intrinsic erodibility.

CONCLUSIONS

The study results show the opportunity that offers NT based cropping system as an alternative to combat water erosion in the mid-slopes of Northern Morocco, yet needing more than 4 years implementation to insure statistical significance. NT helps reducing particle detachability and creating better soil particle cohesion, thus placing a better environment for the development of soil quality, especially in terms of biologic and hydrodynamic properties. On another hand, the study results show the effectiveness of FRN based techniques in assessing soil erosion and adding value to the conventional techniques and indicators. FRN based techniques offer more quantitative, objective and site-specific measurements and evaluation of erosion and soil loss, with interesting return period spans that can range from weeks to decades.

Acknowledgments

The team is thankful to the IAEA RAF project N°5063 staff for the technical and financial support. Acknowledgement is also extended to the INRA/ICARDA collaborative projects that helped to collect data needed for this publication, namely MCGP, CWANA F2R, EiA and Climber.

REFERENCES

1. Lahmar R., Ruellan A. 2007. Dégradation des sols et stratégies coopératives en Méditerranée: la pression sur les ressources naturelles et les stratégies de développement durable. Cahiers Agricultures, 16(4), 318–323.
2. El Jazouli A., Barakat A., Khellouk R., Rais R., El Baghdadi M. 2019. Remote sensing and GIS

techniques for prediction of land use land cover change effects on soil erosion in the high basin of the Oum Er Rbia River (Morocco). Rem. Sens. Appl. Soc. and Env., 13, 361–374.

3. Gourfi A., Daoudia L., Shib Z. 2018. The assessment of soil erosion risk, sediment yield and their controlling factors on a large scale: Example of Morocco. J. of Afr. Earth Sc., 147, 281–299.
4. Sabir M., Maddi M., Naouri A., Barthès B., Roose E. 2002. Runoff and erosion risks indicators on the main soils of the Mediterranean mountains of occidental Rif (Morocco). Proceedings of ISCO XII Conference, Beijing, China 2002, 370–375.
5. Elbouqdaoui K., Ezzine H., Badraoui M., Rouchdi M., Zahraoui M. A., Ozer A. 2005. Approche méthodologique par télédétection et SIG de l′évaluation du risque potentiel d′érosion hydrique dans le bassin versant de l′Oued Srou (Moyen Atlas, Maroc). Int. J. of Trop. Geol., Geogr. and Ecol., 29, 25–36.
6. Mrabet R., Moussadek R., Fadlaoui A., Van Ranst E. 2012. Conservation agriculture in dry areas of Morocco. Field Crops Res., 132, 84–94.
7. Laghrour M., Moussadek R., Mekkaoui M., Zouahri A., Dahan R., El Mourid M. 2015. Impact of no Tillage on physical proprieties of a clay soil in Central Morocco. J. of Mat. and Env. Sc., 6, 391–396.
8. Gonzalez-Sanchez E. J., Veroz-Gonzalez O., Conway G., Moreno-Garcia M., Kassam A., Mkomwa S., Ordoñez-Fernandez,, R., Triviño-Tarradas, P., Carbonell-Bojollo, R. 2019. Meta-analysis on carbon sequestration through conservation agriculture in Africa. Soil and Till. Res., 90, 22–30.
9. Jat R.K., Sapkota T.B., Singh R.G., Jat M.L., Kumard M., Gupta R.K. 2014. Seven years of conservation agriculture in a rice–wheat rotation of Eastern Gangetic Plains of South Asia: Yield trends and economic profitability. Field Crops Res., 164, 199–210.
10. Samal S.K., Rao K.K., Poonia S.P., Kumara R., Mishra J.S., Prakash V., Mondal S., Dwivedi S. K., Bhatt P.B., Naik S.K., Choubey A.K., Kumar V., Malik R.K., Mc Donald A. 2017. Evaluation of long-term conservation agriculture and crop intensification in rice-wheat rotation of Indo-Gangetic Plains of South Asia: Carbon dynamics and productivity. Eur. J. of Agr., 90, 198–208.
11. De Freitas P.L., Landers J.N. 2014. The transformation of agriculture in Brazil through development and adoption of zero tillage conservation agriculture. Int. Soil and Wat. Cons. Res., 2, 35–46.
12. Lal R. 2001. Soil degradation by erosion. Land Deg. and Dev., 12, 519–539.
13. Belmekki M., Mrabet R., Moussadek R., Iben Halima O., Boughlala M., El Gharous M., Bencharki B. 2013. Effects of tillage and cropping systems on the structural stability and soil organic matter in semiarid areas of Morocco. Int. J. of Innov. and Appl. Studies., 4, 322–333.
14. Moussadek R., Mrabet R., Zante P., Lamachere J.M., Pepin Y., Le Bissonnais Y., Verdoodt A., Van Ranst E. 2011. Effet du travail de sol et des résidus de culture sur les propriétés du sol et sur l'érosion hydrique d'un Vertisol Méditerranéen. Can. J. of Soil Sci., 91, 627–635.
15. Laghrour M., Moussadek R., Mrabet R., Dahan R., El Mourid M., Zouahri A., Mekkaoui M. 2016. Long and midterm effect of conservation agriculture on soil properties in dry areas of Morocco. Appl. and Env. Soil Sc. DOI: 10.1155/2016/6345765
16. Moussadek R., Mrabet R., Dahan R., Laghrour M., Lembaid I., El Mourid M. 2015. Modeling the impact of conservation agriculture on crop production and soil properties in Mediterranean climate. Proceedings of the EGU 2015 General Assembly, Vienna, Austria 2015. 1715875M.
17. Bahri H., Annabi M., M'Hamed H.C., Frija A. 2019. Assessing the long-term impact of conservation agriculture on wheat-based systems in Tunisia using APSIM simulations under a climate change context. Sc. of the Tot. Env., 692, 1223–1233.
18. Le Bissonnais Y., Le Souder C. 1995. Mesurer la stabilité structurale des sols pour évaluer leur sensibilité à la battance et à l'érosion. Etude et Gestion des Sols, 2(1), 43–56.
19. Dou Y., Yang Y., An S., Zhua Z. 2020. Effects of different vegetation restoration measures on soil aggregate stability and erodibility on the Loess Plateau, China. Catena, 185, 104294.
20. Wang B., Zhao X., Liud Y., Fang Y., Mad R., Yud Q., An S. 2019. Using soil aggregate stability and erodibility to evaluate the sustainability of large-scale afforestation of Robinia pseudoacacia and Caragana korshinskii in the Loess Plateau. For. Ecol. and Manag., 450, 117491.
21. Martínez-Murillo J. F., Remond R., Ruiz-Sinoga J. D. 2020. Validation of RUSLE K factor using aggregate stability in contrasted Mediterranean ecogeomorphological landscapes (southern Spain). Env. Res., 183, 109160.
22. Vaezi A.R., Eslami S.F., Keesstra S. 2018. Interrill erodibility in relation to aggregate size class in a semi-arid soil under simulated rainfalls. Catena, 167, 385–398.
23. Saygin S.D., Erpul G. 2019. Modeling aggregate size distribution of eroded sediment resulting from rain-splash and raindrop impacted flow processes. Int. J. of Sed. Res., 34, 166–177.
24. Walling D.E., He Q., Quinte T.A. 1995. Use of caesium-137 and lead-210 as tracers in soil erosion investigations. Tracer Technologies for Hydrological Systems. Proced. of the "Tracer technologies for hydrological systems" international symposium, XXI General Assembly of the International Union of

Geodesy and Geophysics, Boulder, Colorado, USA 1995.

25. Mabit L., Benmansour M., Walling D.E. 2008. Comparative advantages and limitations of the fallout radionuclides 137Cs, 210Pbex and 7Be for assessing soil erosion and sedimentation. J. of Env. Radioac., 99, 1799–1807.
26. International Atomic Energy Agency. 2014. Guidelines for using fallout radionuclides to assess erosion and effectiveness of soil conservation strategies. IAEA Editions, Vienna.
27. He Q., Walling D.E. 1997. The distribution of fallout 137Cs and 210Pb in undisturbed and cultivated soils. Appl. Rad. and Isot., 48(5), 677–690.
28. Gaspar L., Navas A. 2012. Vertical and lateral distributions of 137Cs in cultivated and uncultivated soils on Mediterranean hillslopes. Geoderma., 207–208, 131–143.
29. Benmansour M., Mabit L., Nouira A., Moussadek R., Bouksirate H., Duchemin M., Benkdad A. 2013. Assessment of soil erosion and deposition rates in a Moroccan agricultural field using fallout 137Cs and 210Pbex. J. of Env. Radioac., 115, 97–106.
30. Nouira A., Sayouty E. H., Benmansour M. 2003. Use of 137Cs technique for soil erosion study in the agricultural region of Casablanca in Morocco. J. of Env. Radioac., 68, 11–26.
31. Meliho M., Nouira A., Benmansour M., Boulmane M., Khattabi A., Mhammdi N., Benkdad A. 2019. Assessment of soil erosion rates in a Mediterranean cultivated and uncultivated soils using fallout 137Cs. J. of Env. Radioac., 208–209, 106021.
32. FAO. 2006. World reference base for soil resources. ISBN 92–5-105511–4.
33. Le Bissonnais Y. 1996. Aggregate stability and assessment of soil crustability and erodibility : theory and methodology. Eur. J. of Soil Sc., 47, 425–437.
34. Walling D.E., He Q., Zhang Y. 2014. Conversion models and related software: Guidelines for Using Fallout Radionuclides to Assess Erosion and Effectiveness of Soil Conservation Strategies. In IAEA-TECDOC-1741. IAEA Publication, Vienna, Austria, 125–148.
35. Mondal S., Chakraborty D., Bandyopadhyay K., Aggarwal P., Rana D.S. 2019. A global analysis of the impact of zero-tillage on soil physical condition, organic carbon content, and plant root response. Land Deg. and Dev., 31(5), 557–567.