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An Estimation of Corn Yield Losses Arising from Water Shortage by Measuring Thermalized Neutrons

J. Pirvali Beiranvand*, M. Ghamghami, S. Teimouri

Department of Water and Soil Sciences & Engineering, Nuclear Agriculture Research School, Nuclear Science and Technology Research Institute (NSTRI), Iran

ABSTRACT

Droughts are one of the most significant factors disrupting crop growth and development. This study applied a nuclear technique based on thermalized neutrons to estimate maize yield losses arising from water shortages. The biomass consists of water and light hydrogen (1H), which slows down fast neutrons. Hence, thermalized neutrons can be a helpful proxy to determine crop losses. An experiment was conducted with four treatments related to various levels of water stress in three replications. At the end of the maize growing season,, wet weight of the samples was measured, and then the samples were put around an access tube of the Hydro-probe Neutron Meter to count thermalized neutrons. Thereafter, the samples were then transferred to the oven to measure dry weight and in turn, biomass water equivalent (BWE). Findings showed that the average values of the thermalized neutron count ratio were positively and negatively correlated with BWE and damage (%), respectively. The regression models estimating crop losses were cross-validated based on the leave-one-out technique. An absolute mean error equal to 15% and R^2 greater than 0.6 indicate somewhat satisfactory performance of the models. This study was a breakthrough in the feasibility of applying these instruments. Further studies are recommended for practical applications.

***Keywords*:** Damage; Biomass Water Equivalent; Hydro-probe Neutron Meter; Cross-Validation; Neutron-based Tools.

1. Introductions

Crop production is to an enormous extent affected by natural disasters like drought and frost [1]. Extreme climate events disrupt crop growth and development and cause crop losses [2]. Iran is located in a semi-arid and water-scarce region [3] which makes agriculture highly sensitive to climate disasters. For instance, periodic droughts that occurred over the past two decades [4] had socio-economic implications for farmers' income, depending on agriculture, especially rain-fed agriculture [5].

Farmers often implement options to reduce their exposure to unfavorable weather and prevent agricultural damages [6]. Nevertheless, these implementations often are not able to fully cope with climate disasters and agricultural farms are

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*. *Corresponding Author name*: J. Pirvali Beiranvand
E-mail address: jpirvali @aeoi.org.ir

likely suffer to yield losses. In such conditions, a crop insurance contract may compensate farmers [7]. Therefore, estimation of crop losses with as much accuracy as possible has become an imperative issue for designing insurance contracts. Traditionally, methods based on remote sensing are used to estimate crop losses [8]. Though these methods are suitable, designing a damage estimation model based on satellite images requires several years of data which constrains using these methods.

On the contrary, field methods may be alternative suitable tools for this purpose by filling a temporal and spatial scale gap between in-situ observations and remote sensing measurements [9]. Thermalized neutrons can be used to estimate loss amounts in situ. Nuclear tools based on this technique (natural or radioactive thermalized neutrons) have been used for estimating soil moisture before [10, 11]. The idea behind the development of neutron-based techniques is that there exists a good agreement between thermalized neutrons and the number of hydrogen atoms in the environment. Light hydrogen (^1H) has a mass as high as neutrons. Hence, fast neutrons lose their kinetic energy due to elastic collisions with the hydrogen atoms [12]. Water has hydrogen, so it dramatically slows down or thermalizes fast neutrons. The number of thermalized neutrons can be easily measured by a detector [13].

The vegetation is exposed to cosmic-ray neutrons as a result of reactions taking place in the upper atmosphere. Original cosmic-ray particles include protons and helium nuclei. When these nuclei reach the Earth's atmosphere, they collide with air molecules and decompose into protons, neutrons, and other subatomic particles. These neutrons come to the surface and contain high kinetic energy [14]. The cosmic-ray neutron sensor (CRNS) is a tool to detect natural thermalized neutrons [11]. In addition to irrigation management [15-17], cosmic-ray neutrons have applications in aviation studies [18] and studies of other natural disasters like earthquakes [19].

To date, there has been no study on the application of thermalized neutrons for in-situ estimation of crop yield losses. Using neutron-based nuclear tools, this study investigates whether water shortages can affect crop yield (maize in this study).A hydro-probe neutron meter model 503DR (HPNM-503DR) was used for irradiating fast neutrons and fulfilling the study's objectives. The use of the HPNM-503DR in the current study was only appropriate for the feasibility. Obviously, instruments like the CRNS should be employed for operational goals. The HPNM-503DR has been mostly used for measuring soil moisture content (SMC, [13]). It should be noted, however, that the experiment was designed so that this instrument could be used to measure the biomass water equivalent (BWE). According to the methodology presented in the next section, thermalized neutrons could estimate agricultural damages (%). Therefore, this study contributes to the current knowledge of estimating crop losses by identifying and modeling potential relationships between the thermalized neutrons and crop yield losses.

2. Research Theories

Principles of Hydro-probe Neutron Meter

The hydro-probe neutron meter (HPNM-503DR) is a tool applied to measure SMC [13]. This tool employs a radioactivity source containing a mixture of americium-241 and beryllium that emits fast neutrons. A cylindrical probe consists of this source along with a detector of slow or thermalized neutrons which is connected by a cable to other sectors. This probe is lowered into an access tube in the soil while the case remains at the surface [20]. In repeated collisions with nuclei of the same mass as the neutron, fast neutrons emitted from the radioactivity source are slowed or thermalized (like hydrogen). According to [13] on average, 18 collisions with hydrogen are required to thermalize a neutron. This value for other chemical atoms is very much greater than that of hydrogen [21]. Table 1 provides some microscopic properties of ten main elements in dealing with nuclear particles like neutrons [21, 22]. From the table it can be found that hydrogen has the highest elemental stopping power compared to other main elements and thus, the effect of other chemical factors is negligible. In other words, the concentration of thermalized neutrons can be attributed to changes in SMC [23] and consequently, SMC can be measured by counting thermalized neutrons through an empirical calibration. An empirical calibration involves sampling, determining the wet and dry weights of samples, determining volumetric SMC, and finally tracing the curves. (Thermalized neutrons *vs*. SMC). The user guide of [13] explains the application of the HPNM-503DR in more detail.

Hydro-probe Neutron Meter for Study's Objectives

As previously mentioned, the nuclear tool of HPNM-503DR has been employed only for measuring SMC. The other neutron-based nuclear tools like the CRNS use natural instead of radioactivity neutrons that exist in the environment to detect hydrogen sources. In an agricultural farm, there are mostly two main sources of hydrogen i.e., soil moisture and vegetation moisture. Many studies in which the CRNS was employed to monitor SMC [16, 17, 22, 24, etc.] have reported vegetation moisture as noise in recorded data that needs to be removed. This study proposes that vegetation moisture is an important variable that influences yield, particularly when the soil is dry: As a result of natural disasters, crop production per hectare (yield) decreases, as does the moisture level on a farm decreases, resulting in a decrease in thermalized neutrons.

We applied HPNM-503DR to determine potential relationships between thermalized neutrons and vegetation moisture. Herein, the condition for empirical calibration of the tool was similar to that of SMC measuring, but in the vicinity of full-grown biomass and not soil. The radius of neutrons scattering is 30 – 50 cm [13], therefore a hollow with a depth of 90 cm and a radius of 50 cm was built inside the soil and an access tube was installed in the middle of the hollow. Then, over-ground biomass was located around the access tube. Clearly, any thermalized neutron detected by the detector of HPNM-503DR represents vegetation moisture. Regarding the effect of other chemical factors (listed in Table 1) on thermalizing fast neutrons, we assumed these effects were negligible according to microscopic properties provided in Table 1. For instance, the elemental stopping power of H is more than 25 times that for organic matter (C) in plants and for some elements reaches even more than 200 times. Prior to counting thermalized neutrons, the soil in the region of the hollow was entirely dried to avoid plausible errors due to soil moisture. Though this method was non-operational, it was capable of demonstrating the desired relationships.

Table 1. Some microscopic properties of ten main elements in dealing with nuclear particles (adopted by [21, 22]): A- atomic mass (*gmol*$^{-1}$); NC- number of collisions required to thermalize neutrons; ξ- average log decrement of energy per neutron collision; SP- elemental stopping power in *cm*$^{-1}$

Element	A	NC	ξ	SP
H	1.0079	18	1.000	22.016
O	15.9994	149	0.120	0.508
C	12.011	113	0.158	0.875
Si	28.0855	257	0.070	0.151
Na	22.9898	211	0.085	0.277
Ca	40.078	364	0.049	0.139
Al	26.9815	247	0.072	0.109
Fe	55.847	505	0.035	0.411
Mg	24.305	223	0.080	0.297
K	39.0983	355	0.050	0.099

Fundamentals of quantifying potential relationships

Crop yield losses due to either drought or frost mean a reduction in the biological biomass over the surface. Water is a substantial part of biomass.

Here is a term called biomass water equivalent (BWE) required for plant life [16]. BWE is composed of both vegetation moisture and hydrogen present in the biomass [11, 15-17, 24]. The former by measuring wet/dry weight and the latter by identifying the amount of hydrogen and oxygen contained in cellulose can be approximated as follows:

$$BWE = SWB - SDB + f_{WE} \times SDB \qquad (1)$$

where SWB and SDB are standing wet and dry biomass respectively (kg/m^2), and f_{WE} = 0.494 that is the stoichiometric ratio of H_2O to organic carbon molecules in the plant assuming organic carbon is generally cellulose $C_6H_{10}O_5$ [11]. The stoichiometric ratio takes into account the percentage of hydrogen that is in dry matter [22]. Other chemical sources of hydrogen, whether organic or mineral, are small enough to be ignored in the process of empirical calibration. Based on the rule of mass conservation, we can delineate the following relationships:

$$Damage \propto BWE \quad , \quad BWE \propto Nr \qquad (2)$$

$$Damage\% = 100 - \left(\frac{Y_a - Y_{min}}{Y_{max} - Y_{min}}\right) \times 100 \qquad (3)$$

where Y_a, Y_{min}, Y_{max} are actual, minimum, and maximum yield, respectively, in the field. Nr is a dimensionless variable characterizing thermalized to fast neutrons count ratio [24, 25]. The number of fast neutrons is determined by measuring neutrons received by the detector of HPNM-503DR in the vicinity of pure water. An experiment was carried out to calibrate equations corresponding to the relationships in (2) on maize as is described in the following subsection.

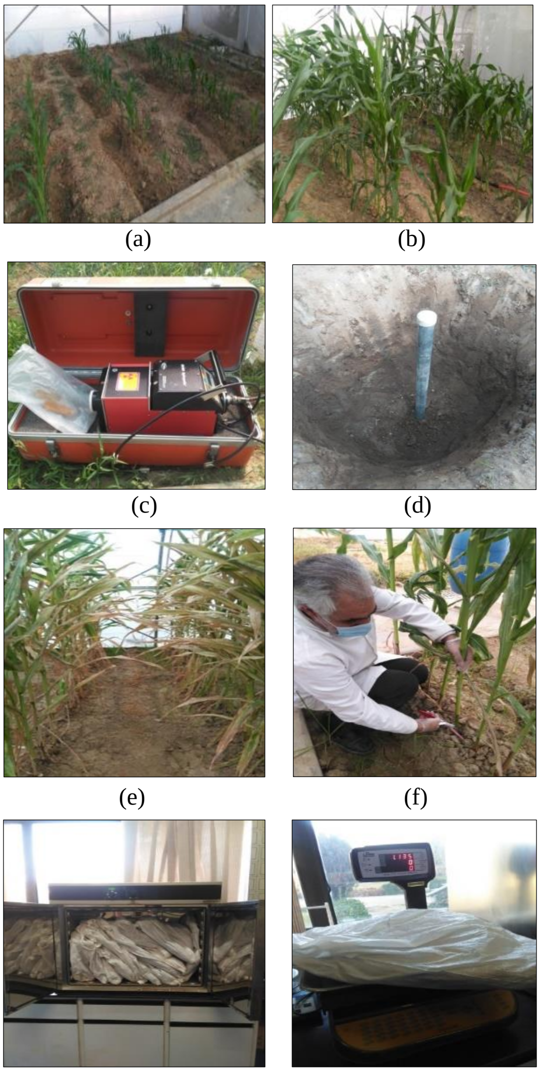
3. Experimental

To achieve the study objectives, an experimental design was conducted in the research greenhouse of the Nuclear Agriculture Research School located in Karaj, Iran. A completely randomized design (CRD) was implemented on the maize with the four treatments relevant to water stress defined as no stress (fully irrigated: $\frac{4}{4}$), low stress (partially irrigated: $\frac{3}{4}$), moderate stress (partially irrigated: $\frac{2}{4}$), and severe stress (partially irrigated: $\frac{1}{4}$), in three replications. The distance between treatments was around 1.5 m to prevent water infiltration among different treatments. In each plot, thirteen seeds were planted at a distance of 10 cm. The total area of the experiment was 27.5 square meters. Water stress was exerted throughout the growing season except for the early stages of growth (plant establishment on the soil surface). According to FAO-56 Penman-Monteith method [26], the water requirement of maize in no-stress conditions was calculated to be 8500 m3/ha, and treatments were irrigated as flood irrigation. Given the soil properties, the fertilization process was performed for all treatments in the same way. Table 2 indicates dates associated with planting, harvesting, phonological events, and irrigation.

Table 2. Sharp dates during the maize growing season.

Phonological stages	Date	Irrigation date	Corresponding stage
Planting	2021/14/08	2021/14/08*	Planting
Emergence	2021/25/08	2021/27/08*	Emergence
Trifoliate	2021/01/09	2021/07/09	Trifoliate
Leaf appearance	2021/09/09	2021/17/09	Leaf appearance
Inflorescence	2021/12/10	2021/28/09	Leaf appearance
Flowering	2021/18/10	2021/09/10	Leaf appearance
Silking	2021/29/10	2021/19/10	Flowering
Milky	2021/07/11	2021/30/10	Silking
Dough	2021/19/11	2021/09/11	Milky
Harvest	2021/01/12	*Irrigation without water stress	

Once the maize ripened, sampling was started and three shrubs were randomly selected from each plot of CRD. Then, the samples were transferred to the hollow for counting thermalized neutrons. Hence, after putting the samples around the access tube of the HPNM-503DR, neutrons colliding with the light hydrogen atoms present in the plant biomass were counted. In addition, the wet weight of the samples was measured and the samples were transferred to an oven in the temperature range of 75-85 ºC. After 120 hours, the dry weight of the samples was measured to estimate BWE according to Eq. (1). Many attempts were made to control the experiment (irrigation scheduling, fertilizing, weed controlling, etc.), and therefore, any decrease in yield could be attributed to water stress. Fig. 1 provides visual documentation from various stages of the project.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 1. Various stages of the project: (a) plants in the phenologicalstage of trifoliate; (b) plants in the middle of leaf appearance; (c) a Hydro-probe Neutron Meter model 503DR; (d) the experiment site: a hollow within the soil in which there is an access tube for counting thermalized neutrons; (e) plants in the stage of ripening; (f) randomly sampling from over-ground biomass; (g) samples in the oven; and (h) calculating wet/dry weight of samples.

3. Results and Discussion

Safety

A dosimetry experiment was performed to account for the safety of neutrons irradiated from the radioactivity source during experiments evaluating the relationships between BWE/damage and thermalized neutrons. This experiment was done in two scenarios, namely, inside the shield and at a depth of 40 cm. The results of the experiment when the HPNM-503DR was working are presented in Table 3. According to the table, irradiated neutrons had no harmful biological effects on humans. This guarantees0the safety of the experiment because measured dosages were far less than momentary allowance dosages.

Table 3. Dosimetry analysis of experiment site.

Situation	Measured dose	Yearly allowance dose	Momentary allowance dose
Shield inside	20 µSv/hr*	20 mSv/hr	2 mSv/hr
Depth 40 cm	2 µSv/hr	20 mSv/hr	2 mSv/hr

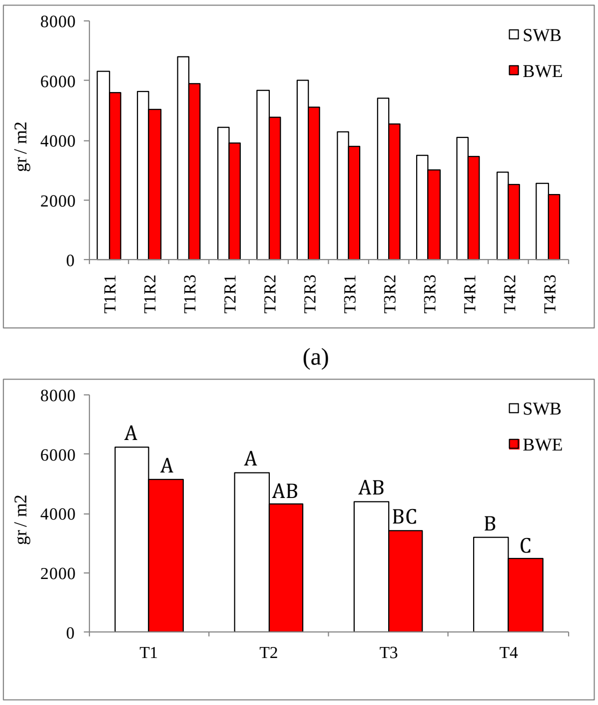
* Sievert in hour, unit representing dose amount. A sievert is a very large unit of dose and often millisieverts (mSv) or microsieverts (µSv) are used.

Calibration

The SWB/SDB was obtained by multiplying the mean of wet/dry mass of three samples by the number of plants grown per plot and then dividing by the area of each plot (1.5 m^2). The BWE values, for each plot separately, were calculated using Eq. (1). Fig. 2a shows the changes in the SWB (for maize, which is equivalent to yield) and the BWE in different treatments and replications. From the figure, it can be found that as averaged over all plots, more than 86% of the biomass weight at the ripening stage includes water. This indicates how much the quantity of BWE can be helpful in estimating damage.

Fig. 2a illustrates that water stress imposed at three levels has reduced the maize yield and in turn, the

BWE. An ANOVA was done to compare SWB and BWE data and to assess possible differences among treatments and replications (Table 4). The results show that the differences among treatments are significant at 5% and 1% levels for SWB and BWE, respectively. Fig. 2b also indicates statistical significance. On the contrary, differences among replications are not significant. The lowest yield was associated with the partially irrigated treatment (T4R3), around 2.5 kg biomass per m2; the highest yield was associated with the full irrigation (T1R3), about. These differences can also be perceived regarding the BWE.



(a)

(b)

Fig. 2. Changes the SWB and the BWE in different treatments and replications (a), and ANOVA results indicating statistical significances (b).

Table 4. ANOVA results.

Source	Dependent variable	F	P-value
Treatments	SWB	6.093	0.03^{*}
	BWE	11.257	0.007^{**}
Replications	SWB	0.046	0.956
	BWE	0.039	0.962

* significant at 5% ** significant at 1%

By estimating the damage (%) from the yield (according to Eq. 3), it was found that the correlation between BWE and the amount of damage is approximately -0.997. It indicates that applying the technique of thermalized neutrons would be asuitable procedure for estimating damage. Fig. 3 shows the correlations of the thermalized neutron count ratio (Nr) with the BWE (top diagram) and the damage (%) (bottom diagram) at different depths of 40, 60, and 80 cm. Nr was obtained by dividing the number of thermalized neutrons by the number of fast neutrons -equivalent to thermalized neutrons exposed to pure water- which was about 18,800 neutrons. For example, regarding the T1R1 treatment at a depth of 80 cm, the number of thermalized neutrons was equal to 840 neutrons and therefore, Nr equaled0.0447. The BWE values were positively correlated with Nr. These correlations were not significant at depths of 40 and 60 cm, and were significant at depth of 80 cm. This depth had a coefficient of determination (R2) of around 0.81. The reason for counting neutrons at three different depths was to determine the geometry of the biomass in the hollow. Therefore, an average of three depths was considered for the final assessment. Circular black dots are the Nr averaged at three depths, which shows the all-purpose relationship between the BWE in different treatments and the Nr. As can be seen, this relationship is significant with an R^2 of around 0.6. Unlike the BWE, the damage (%) values were negatively correlated with Nr i.e., the greater the damage due to water stress, the lower the Nr, because there was less BWE at the test site. Similar results to the BWE were obtained regarding the damage such that R^2 obtained from the relationship between the mean Nr and the damage (%) was around 0.64. These findings confirmed that the thermalized neutrons are capable of estimating the percentage of damage.

Cross-validation

To cross-validate the regression models constructed for estimating damage (%), we used the leave-one-out technique [27]. In these models, Nr was regarded as the independent variable. The graph in Figure 4 shows observed versusthe cross-validated damage (%) values. Whiskers show a 95% confidence interval determined by randomly running the models. The absolute mean error (MAE) criterion was estimated to be 15% indicating relatively satisfactoryperformance of the models. Additionally, two other criteria were used to evaluate the models as shown in Table 5. The second column in this table (from the left) shows the equations obtained given the target (the first column). The third column shows the adjusted R^2 of the models which is around 0.6 (except for target T4R1 which is more than 0.8). Also, the fourth column shows the p-value of the Shapiro-Wilk (S-W) test [28] indicating the validity of the regression models. This test determines whether the distribution of residues (errors) is random or systematic. If the p-value of this test is less than 0.05 (H_1 assumption), it means that the distribution of residues is systematic and therefore the models are not valid. As can be seen, all models are valid at the 5% level according to this test because the p-values of all models are more than 0.05.

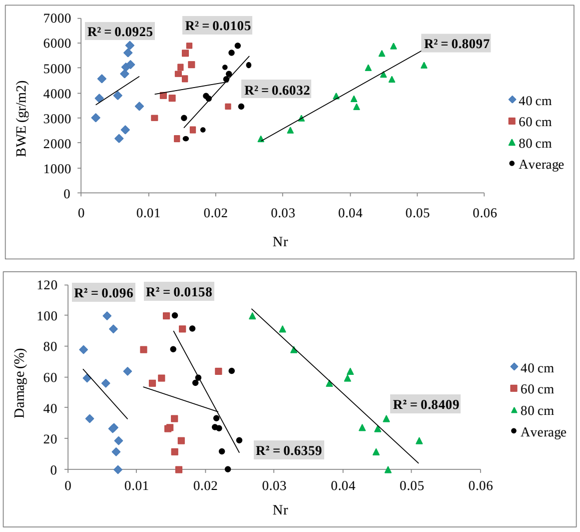


Fig. 3. Relationships among the BWE, Nr, and damage.

In summary, the findings show that the count of thermalized neutrons detected by an onboard detector is a suitable proxy to estimate crop yield losses caused by natural hazards like drought and frost. Similar to many studies e.g., [16] and [22], we found that there is a significant relationship between BWE and thermalized neutron count ratio. We used this aspect to estimate damages which distinguishes our study from other works. However, the MAE of 15% must be improved. To improve the performance of the developed models for estimating damage, the sources of error or uncertainty of the models should be identified. One of these sources is small sample size due to limitations. Other sources of errors includeto random sampling, non-uniform drying of samples, etc., which can be reduced by increasing the accuracy and the precision of experiments.

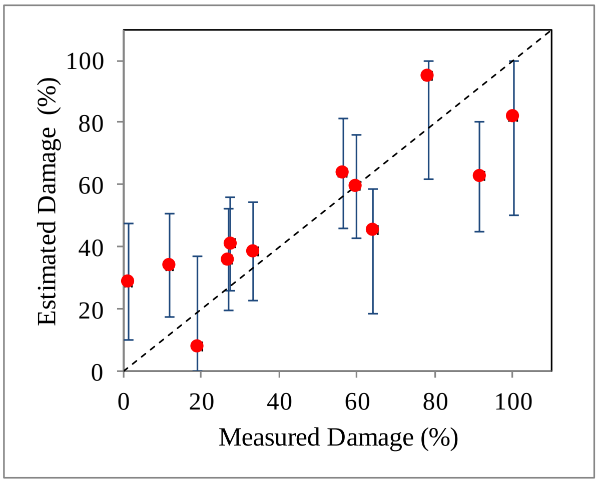


Fig. 4. Measured vs. estimated damage (%) values based on the leave-one-out cross-validation technique.

4. Conclusion and Outlook

The current preliminary study presents a new method for estimating crop losses arising from water shortages; the application of thermalized neutrons. For this purpose, samples harvested from treatments under water stress at different levels were exposed to fast neutrons. The relationship between Nr and BWE/damage was investigated by counting thermalized neutrons. The results showed that the technique of thermalized neutrons can be used for in situ estimation of agricultural damages. In this study, we used a neutron probe for producing radioactive radiation. Using this probe, it was largely feasibleto extract these relationships. Other nuclear tools such as the cosmic-ray neutron sensor (CRNS) could be used for operational applications for two reasons: the first, radioactive radiation has dangerous biological effects on humans when long-time use, and the second, it covers a small spatial range and therefore, proper field estimates for large farms cannot be fulfilled. The CRNS uses natural neutrons in the environment and has been widely used to monitor soil moisture and irrigation scheduling. We recommend further studies to determine coefficients of linear or nonlinear equations between CRNS-recorded thermalized neutrons and yield obtained at the end of the growing season. For this purpose, the following considerations should be considered:

Table 5. Equations and measures evaluating the regression models.

Target	Equation	Adj. R^2	P-value
T1R1	%Damage = 208.6-7788.3×Nr	0.630826	0.416918
T1R2	%Damage = 213.6-8070.7×Nr	0.637253	0.507484
T1R3	%Damage = 202.2-7448.2×Nr	0.616414	0.259461
T2R1	%Damage = 214.9-8186.4×Nr	0.630596	0.252155
T2R2	%Damage = 214.1-8127.8×Nr	0.631331	0.403336
T2R3	%Damage = 232.8-8994.4×Nr	0.618784	0.255432
T3R1	%Damage = 218.3-8323.3×Nr	0.637878	0.391211
T3R2	%Damage = 212.9-8056.2×Nr	0.627726	0.515511
T3R3	%Damage = 222.8-8620.3×Nr	0.613777	0.089866
T4R1	%Damage = 244.1-9831.1×Nr	0.83799	0.343138
T4R2	%Damage = 199.7-7559.9×Nr	0.628139	0.187939
T4R3	%Damage = 196.9-7379.4×Nr	0.531507	0.169842

- Several farms with different climatic conditions must be selected in all of which a certain cultivar has been planted. The greater the number of farms, the broader the information diversity;
- Up to ten days - two weeks before the neutron count, the farms should not be irrigated or not experience rainfall (note that a country like Iran mostly experiences rainfall from October-November to March-April which this period does not cover the harvest time of most crops). Otherwise, the soil moisture effect should be removed by sampling the soil and determining the volumetric moisture of soil [13];
- The effect of air humidity should be removed in each region [29]. This will be possible by assigning correction coefficients based on the climatic characteristics of each region.
- Determining whether the damage is due to natural disasters or farm mismanagement can be carried out by combining the developed models with local meteorological data.
- For crops with differences between biological and economic yield, such as wheat and soybean, it is necessary to separate these components. In addition, it is necessary to examine the relationship between Nr and economic yield aiming to design insurance contracts. Here, the over-ground yield should be indirectly correlated with Nr through some indices such as the harvest index [30].

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