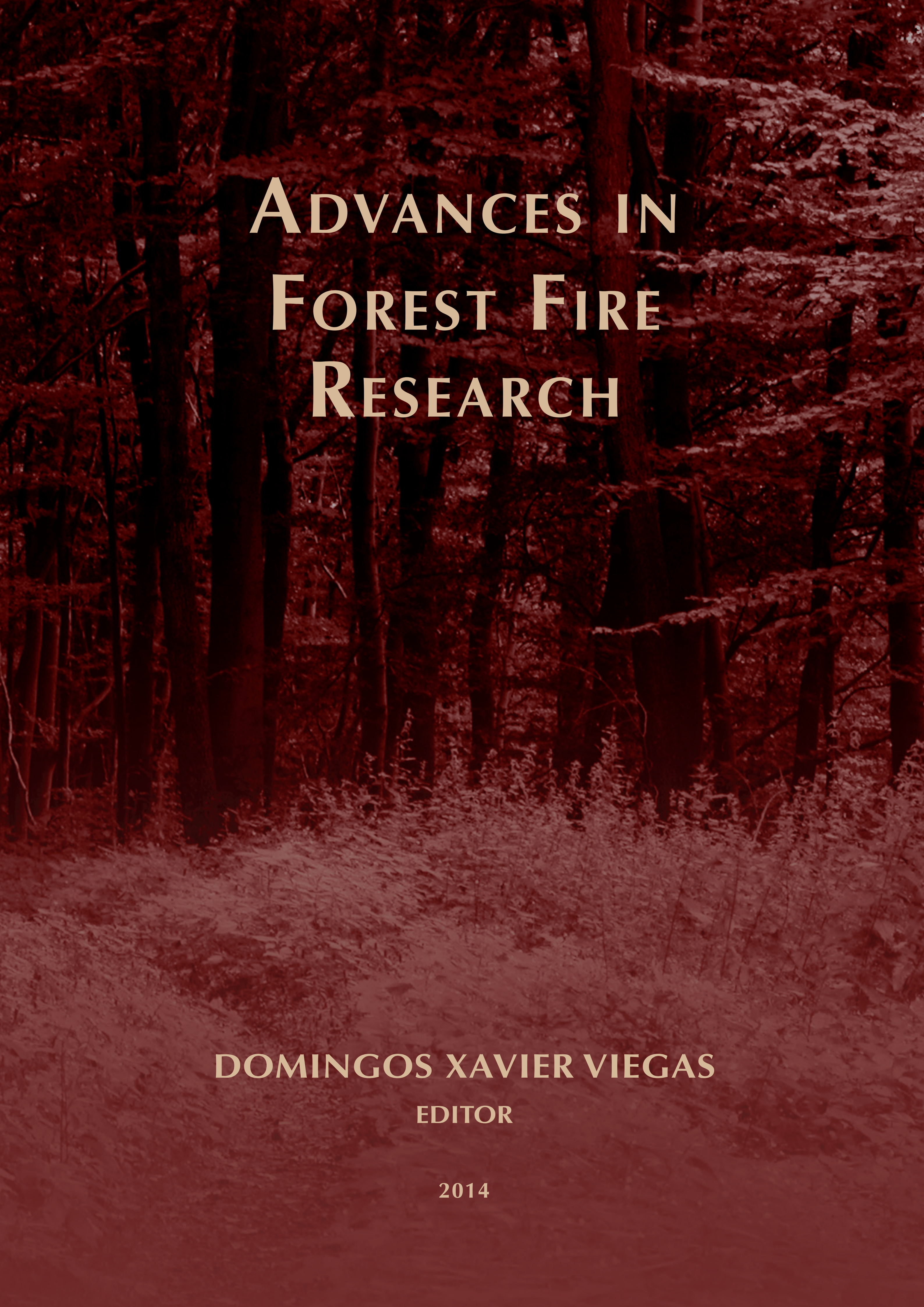

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Evaluation of a system for automatic dead fine fuel moisture measurements

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Abstract
Dead fine fuel moisture content is a key parameter for wildfire ignition and behaviour: the higher the fine fuel moisture content, the more activation energy has to be spent on the evaporation of this moisture before the fuels can ignite and release their energy of combustion. Thus, high fuel moisture leads to a lower probability of ignition and a more moderate fire behavior.
These facts have been recognized for a long time and fine fuel moisture has become an essential part of several fire danger rating systems (e.g. 1- and 10-hour dead fuel moisture in the National Fire Danger Rating System (NFDRS) and Fine Fuel Moisture Code in the Canadian Forest Fire Danger Rating System (CFFDRS)). Additionally, dedicated fine fuel moisture models are available as well.
Nevertheless, direct information on dead fine fuel moisture can be valuable for monitoring, scientific research as well as during exceptional conditions, e.g. extreme fire danger with exceptional temporal or spatial distribution of fire danger, for the management of large wildfires. However, dead fine fuel moisture measurements are hard to obtain since common methods involve manual sampling in the field and potentially oven-drying, adding a time delay before the results become available.
In this study, a thorough evaluation of the Campbell Scientific, Inc. instrumentation for automated 10-hour dead fuel moisture (CS506-L fuel moisture sensor) has been carried out. Ten fuel moisture sensors and associated *Ponderosa pine* dowels were obtained and subjected to tests in a constant climate chamber as well as at two field sites in Central Europe for one fire season. The comparability of the values determined from these ten different dowels as well as a potential influence of weathering were investigated along with correlations to manual-gravimetric fuel moisture.
Results show that dowel-to-dowel comparability is relatively good but may be further increased by additional calibration. In the field, there was an excellent correlation between 10-hour fuel moisture as measured by the CS506-L sensors and fast-drying dead fuels such as needle litter and dead grass (R^2 0.81 and 0.82, respectively). Weathering effects during the study period had no major influence on sensor performance.

***Keywords**: fine fuel moisture, 10-hour fuel moisture, automatic measurement*

1. Introduction

Fine fuel moisture has been recognized as a key parameter for forest fire danger, ignition and behaviour and thus also for fire-fighting (Pyne *et al.* 1996). This is because most fires start and spread, at least initially, in fine fuels located on the forest floor and their water content plays an important role for ignitability and combustibility. Wet fuels tend to ignite less easily and to burn more moderately (if there is sustained combustion at all), since a large amount of energy has to be spent on evaporating the moisture (Pyne *et al.* 1996). This additionally leads to a cooling effect (Britton *et al.* 1973) and to a dilution of combustible gases (Chandler *et al.* 1983). Thus, fine fuel moisture is an important parameter in the field and the basis of several forest fire danger rating systems, such as the National Fire Danger Rating System (NFDRS, USA (Bradshaw *et al.* 1983)) and the Canadian Forest Fire Danger Rating System (CFFDRS (Van Wagner 1987)).
Despite its high significance, there is no straightforward way of measuring fine fuel moisture automatically in the field. Gravimetric measurement following manual sampling is the standard procedure (Britton *et al.* 1973; Norum and Miller 1984; Viegas *et al.* 2006), which however requires

a person to travel to the respective field site(s) and to take fuel samples. These samples need to be transported back to a laboratory, weighed wet, oven dried and weighed again in a dry state. In addition to the multitude of steps required, drying time (24 hours in many studies) leads to an additional delay before the fuel moisture measurements become available, rendering them useless for any immediate prevention or fire management decisions.

Several methods have been developed to overcome these problems. One of them is based on an observation made by early US fire researchers in Scandinavia, where local foresters used wood as a reference material that was easier to observe that the fine fuels (Hardy and Hardy 2007). This method was extended by Gisborne (1933), who set up rules to standardize the so-called fuel moisture sticks and trimmed them to exactly 100 g dry mass (Fischer and Hardy 1976; Hardy and Hardy 2007). Following this standardization, moisture content of the reference sticks could be determined using a simple balance in the field. Later on, the dead fuel moisture components of the NFDRS were based on those measurements and on theoretical considerations for drying and wetting of cylindrical objects (Bradshaw *et al.* 1983; Burgan 1988; Cohen and Deeming 1985). However, an influence of wood decay on the long-term stability of the measurements was detected (Haines and Frost 1978). Finally, several instrument manufacturers (e.g. Campbell Scientific (North Logan, UT, USA), Vaisala (Helsinki, Finland) and Forest Technology Systems (Victoria, BC, Canada)) have found ways to automatically measure the stick's moisture content, e.g. using capacitive sensing. Although some of the manufacturers had to adapt the stick dimensions to their techniques, this widely increases the potential use of fuel moisture measurements. For example, automated fuel moisture sensors are part of many RAWS stations in the US (NWCG 2009). Nevertheless, the precision, reliability and long-term performance of these systems remain somewhat dubious (Gibos 2010) and are examined in this study.

2. Methods

The measuring system developed by Campbell Scientific consists of a fuel moisture stick (26601 CS506, also called "dowel") connected to a so-called fuel moisture sensor (electronics unit, CS506-L) and associated data logger. In order to evaluate the measuring system, a total of 8 fuel moisture sensors, 10 fuel moisture sticks and three data loggers (CR800) were acquired. The fuel moisture sticks are made of *Ponderosa pine* wood into which two stainless steel electrodes are pressed and secured by cable ties. They have a nominal dimension of 1.3 cm (0.5") diameter and 50.8 cm (20.0") length and are meant to represent the 10-hour fuel moisture class of the NFDRS. The RMS error and maximum usage time reported by the manufacturer are 0.75-2.27% and one season, respectively. The sensors were tested in two forest sites in Bavaria, southern Germany, for one fire season, during which manual gravimetric measurements of fine fuel moisture were made regularly. Before and after the field tests, reference measurements were made in a climate chamber. At the end of the study, the fuel moisture sticks were separated in hygroscopic (wood) and non-hygroscopic (electrodes and cable ties) material and the wood parts were oven-dried.

2.1. Reference measurements in the climate chamber

In the climate chamber, only one fuel moisture sensor (electronics unit) was used, to which the 10 fuel moisture sticks were connected sequentially. This was performed regularly during the two desorption runs before and after the field measurements, which included the following conditions: soaking the fuel moisture sticks for one hour, subjecting them to 23°C and 90, 80, 70, 60, 50, 40, 30, 20% relative humidity until equilibration before the field measurements and to 23°C and 90, 55, 20% relative humidity (shortened desorption run) after the field measurements. Equilibration of the sticks' moisture content was assessed using both the automated measurements and additional manual weighing. The climate chamber was of a walk-in type (3.9 m^2 floor space) and had a typical accuracy of ±0.2°C and ±5% relative humidity, respectively.

2.2. Field measurements

Following the initial climate chamber tests, the two forest climate stations “Altdorf” (49.4175° N, 11.3125° E, approx. 15 km east of Nuremberg, pure Scots pine (*Pinus sylvestris*) stand) and “Freising” (48.4102° N, 11.6595° E, approx. 30 km north of Munich, mixed European beech (*Fagus sylvatica*) and pedunculate oak (*Quercus robur*) stand) of the Bavarian State Forest Institute (Bayerische Landesanstalt für Wald und Forstwirtschaft, LWF) were equipped with three fuel moisture sensors and sticks each. The measurements were carried out from end of March until end of October 2013, and after each third of the measuring period, one fuel moisture stick was exchanged by a spare that had been stored in a laboratory for this purpose. The fuel moisture sensors were mounted according to the manufacturer’s instructions at a height of 30.5 cm (12”) above the ground, facing south. The setup at the Altdorf station is shown in Figure 1 as an example. Their values were measured and stored at 15-minute intervals, according to the measurement intervals of the existing forest climate stations.

Figure 1. Arrangement of fuel moisture sticks at the forest climate station Altdorf.

During the measuring period, fuel moisture samples of litter (Altdorf and Freising) and dead grass from the previous season (Altdorf only) were taken regularly. While it was our aim to sample in the early afternoon, at least weekly during wet periods and at least every other day in dry periods, a certain variation occurred due to the availability of sampling personnel. Additionally, dry grass sampling at Altdorf had to be terminated in the end of August as the grass had decayed in a way that it was no longer relevant to fire danger and that sampling became impossible. For each day and fuel, three samples were taken, which were stored in air-tight polypropylene bottles and shipped to the laboratory within a maximum of 7 days. The fuel moisture was calculated gravimetrically (in % of dry mass), following oven-drying at 105°C for 24 hours.

2.3. Data analysis

The data thus gathered were combined, processed and analyzed in a way that the relationship of the automatically measured fuel moisture values to relative humidity and gravimetric stick moisture in the climate chamber before and after the field measurements could be shown. The field measurements themselves are presented as progressions of the measured stick moisture over time and as correlations of stick moisture and gravimetric fine fuel moisture content. Linear regressions are used for showing and modelling relationships between the different measurement variables, where appropriate. All data processing, statistics and plotting were performed in R, version 3.0.3, and its packages xlsx, doBy, and RODBC.

3. Results and discussion

3.1. Reference measurements before the field campaign

Before the field campaign was started, a relatively high resolution desorption run was carried out in a climate chamber in order to compare the fuel moistures of each stick, measured both by the automatic system and gravimetrically. The gravimetric moisture values were obtained by weighing the fuel moisture sticks repeatedly and combining these values with the mass of the non-hygroscopic material and the oven-dry mass of the wood determined at the end of the study. Results for both automatically measured and gravimetric moisture of the sticks are shown in Figure 2.

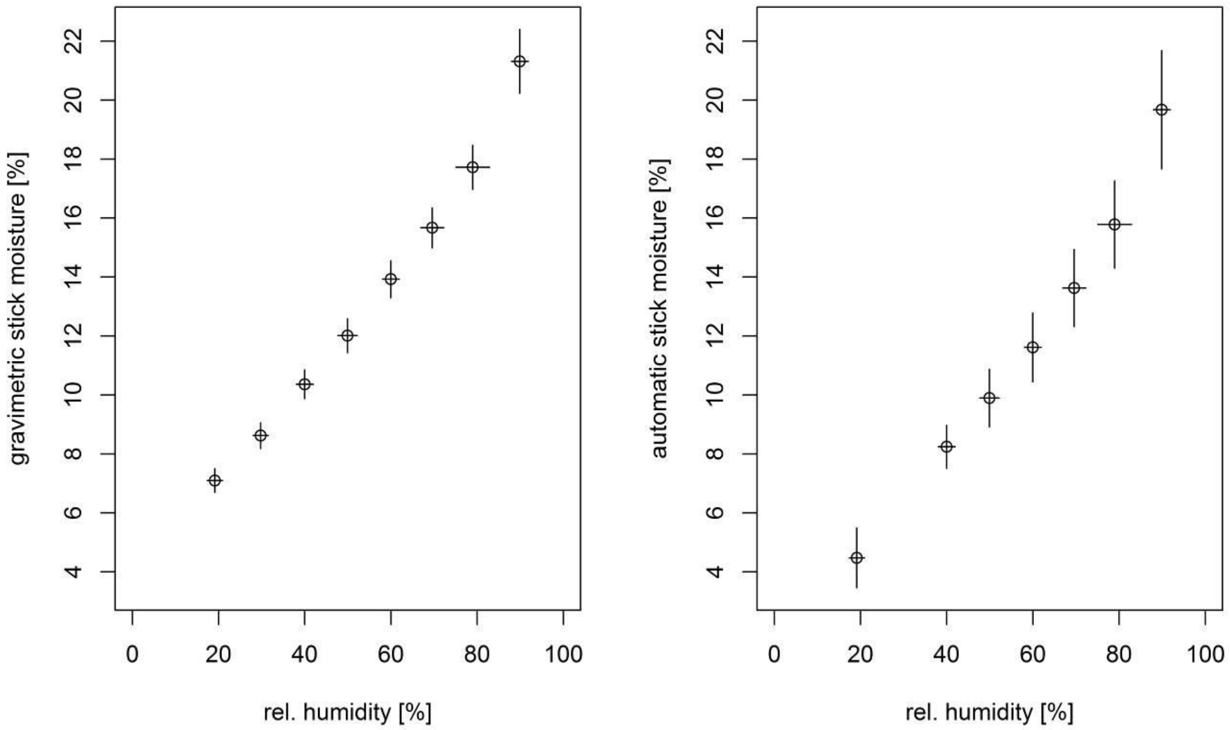


Figure 2. Results of the initial climate chamber desorption run. Left graph: gravimetric fuel moisture, right graph: fuel moisture as measured by the automated system.

The left graph in Figure 2 represents the gravimetric fuel moisture during the desorption run and is thus a classic sorption isotherm. In contrast to isotherms from literature for wood (Kollmann *et al.* 1986; Forest Products Laboratory 1999) and fine fuels (Van Wagner 1972; Anderson 1990; Blackmarr 1971; Lopes *et al.* 2010), it lacks the typical sigmoid shape. Apart from this, an increasing standard deviation with increasing relative humidity can be observed. Comparing this to the automated measurements in the right chart of Figure 2, their absolute values are not identical to the gravimetric measurements and the standard deviations are substantially higher. This is not surprising as the gravimetric technique is by far more accurate than the capacitive sensing of the automated measurement. Additionally, the dry mass of the sticks (not shown) had a variation >5%, influencing the automated measurements as they in fact react to the density surrounding the electrodes.

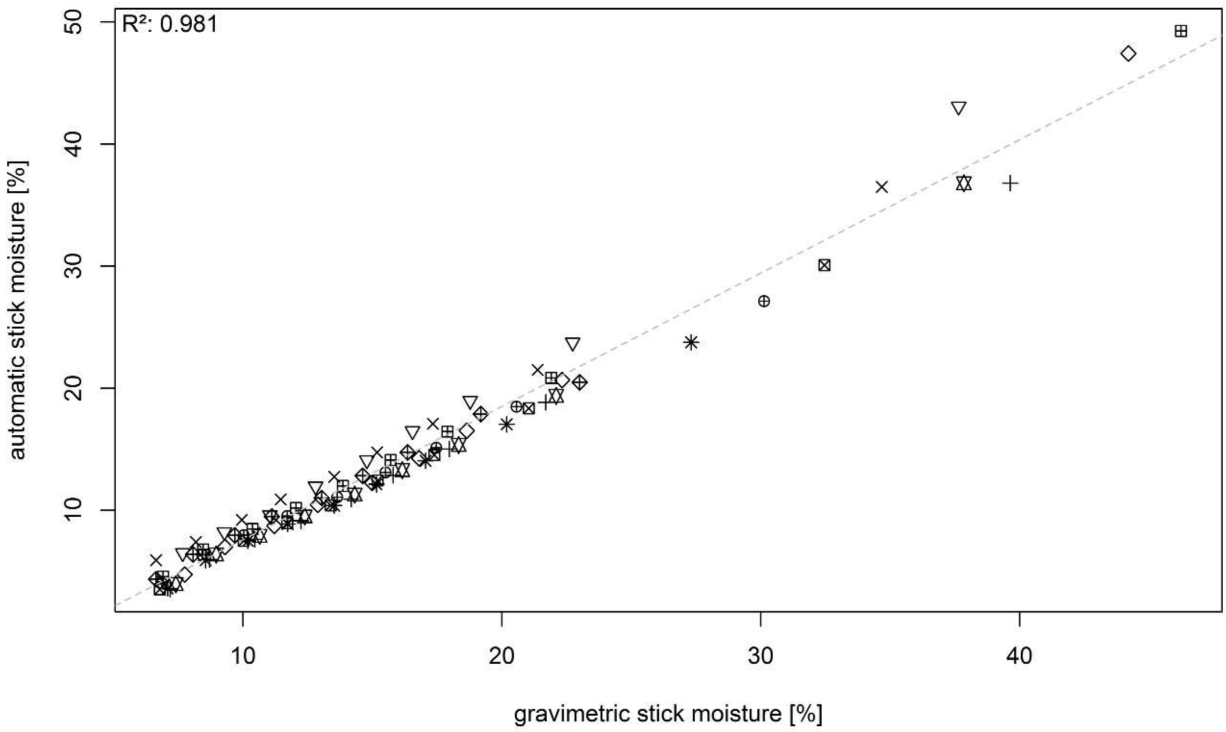
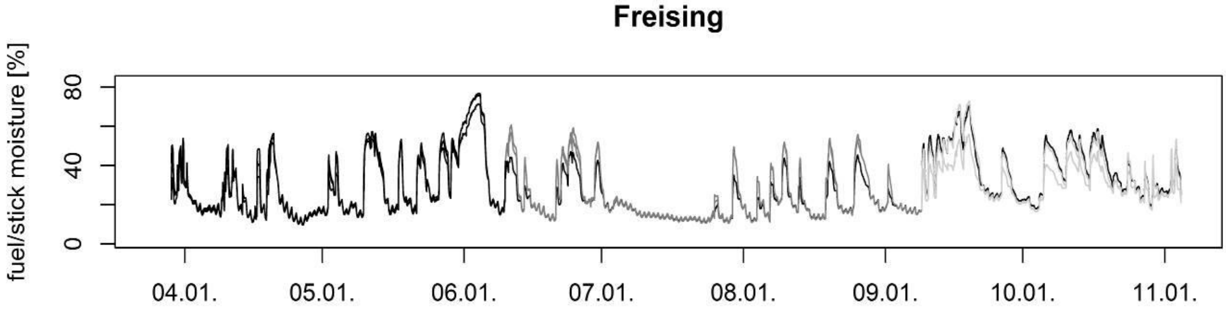


Figure 3. Automated fuel moisture values of the initial desorption run in dependence of the gravimetric fuel moisture. The different symbols correspond to the individual fuel moisture sticks.

When the automated values are shown in dependence of the gravimetric fuel moisture (Figure 3, including the values of the soaked sticks), a distinct and highly significant correlation of these values (R^2 0.981) is obvious. However, not all individual fuel moisture sticks follow a common regression line. Linear calibration for each stick can be used to correct this and to make the absolute automated fuel moisture values identical to the gravimetric moisture content of the sticks (not shown). However, this procedure is very laborious, as a full desorption run and an estimation of the stick's dry mass is necessary.

3.2. Field measurements

The progression of the automatically measured fuel moisture during the field campaign is shown in Figure 4. Whenever a new fuel moisture stick was used, all values until the first substantial precipitation event were removed. It can be seen that the accordance of the individual fuel moisture sticks is quite good and that there are no obvious shifts when the sticks were exchanged (lighter shades of gray represent longer ageing and use in the field). However, high moisture contents are usually accompanied by a higher variation from stick to stick than low moistures. During dry conditions, a daily cycle of fuel moisture can be observed that corresponds to textbook examples (cf. Pyne *et al.* 1996).



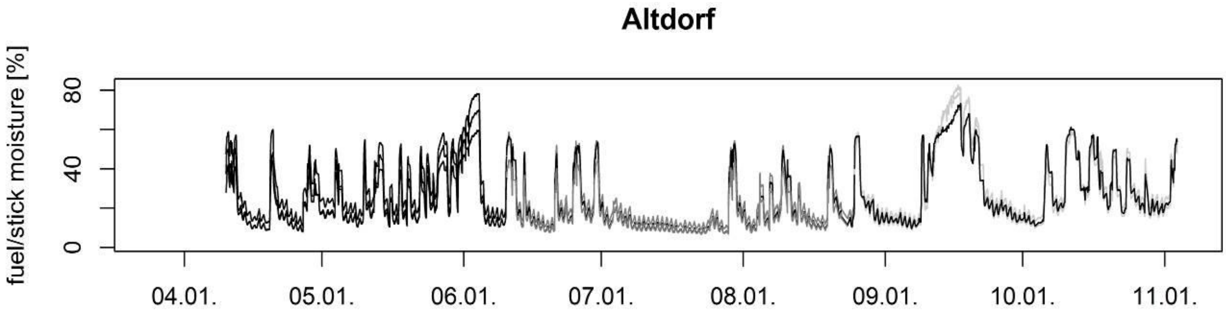


Figure 4. Progression of fuel moisture during the field measurements. Lighter shades of gray represent longer ageing of the sticks and thus longer use in the field, i.e. black-coloured lines represent fuel moistures that have been determined during initial exposure of any fuel moisture stick; dark gray lines an extended exposure of another third of the measuring period and light grey lines an exposure over the whole measuring period.

When the automated fuel moisture measurements are compared to simultaneously sampled gravimetric values of local dead fine fuels (Figure 5), correlations of varying strength and significance can be observed. For the thick, rather slow drying layers of European beech and pedunculate oak leaves at Freising, R^2 of the linear regression is smaller (0.44) than for the values of Scots pine litter and dead grass from the previous season (Altdorf, R^2 0.81 and 0.82, respectively). These are good, despite the fact that the type of material, dimensions, and arrangement are substantially different.

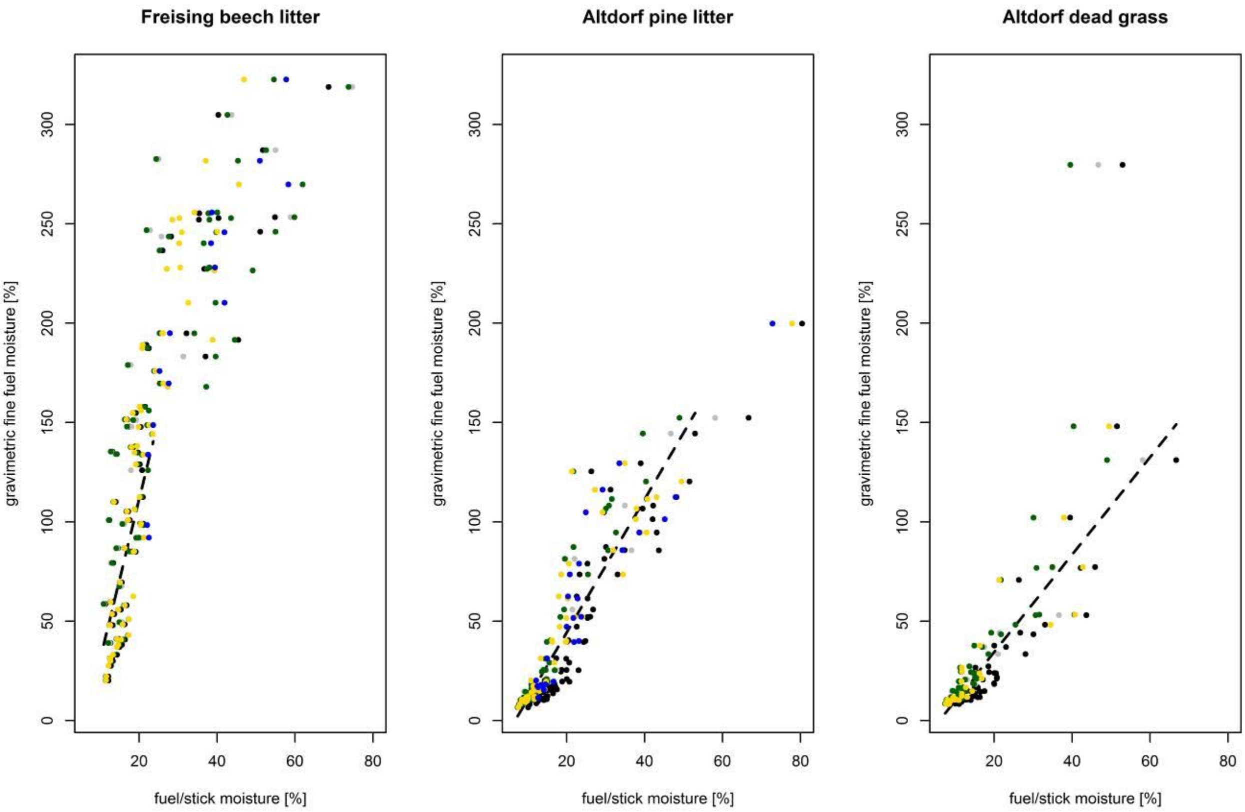


Figure 5. Correlations of (left to right) automatically measured and manually determined fuel moisture for European beech (Freising) and Scots pine (Altdorf) litter, as well as dead grass from the previous year (Altdorf).

3.3. Reference measurements after the field campaign and long-term stability

Besides comparing the continuity of the measuring signal when the fuel moisture sticks were replaced in the field (cf. Figure 4), additional reference measurements were made in the climate chamber after the field exposure of the sticks. These are compared to the initial desorption run in Figure 6, where the initial values are shown in black, the associated confidence intervals as dashed orange lines and the final reference values as red circles.

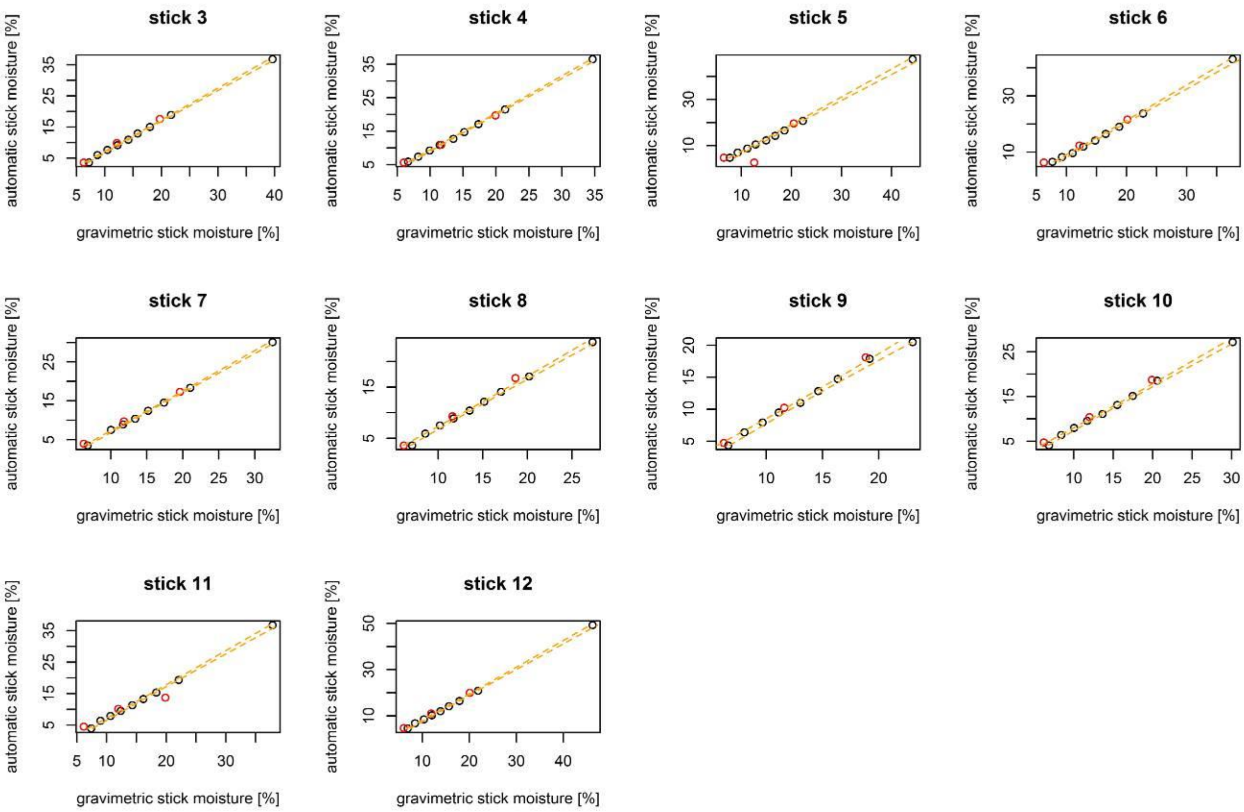


Figure 6. Correlations of automatic and gravimetrically measured fuel moisture of the sticks before (black circles) and after (red circles) the field campaign, determined in steady-state conditions in the climate chamber. The orange dashed lines correspond to the confidence interval of the initial measurements.

Except for very few outliers that were probably caused by measuring errors, no relevant differences in the signal before and after the field exposure can be discovered. Thus, the long-term stability of the fuel moisture sticks can be constituted as sufficient for (at least) one fire season under conditions similar to this central European setting.

4. Conclusions

This study was carried out to evaluate the performance of the automated Campbell Scientific fuel moisture measurement system (CS506-L). Using measurements in controlled environments, at field sites and a comparison to manual sampling and gravimetric moisture content determination, it could be shown that the stick-to-stick deviation is tolerable, no relevant ageing effects are expected to occur during one fire season and there is a correlation of the automated 10-hour fuel moisture values to common dead fine fuel moisture (ranging from R^2 0.44 to 0.88 depending on the type of fuel). Overall, this system is a satisfactory option when a direct measure of an (analogous) fuel moisture value is required, yielding values that can be deemed at least acceptable for this hard-to-measure parameter. The automated operation as well as the possibility for immediate data transmission and availability is a great benefit of this system. However, even changing the fuel moisture sticks annually is rather cost-intensive when the original fuel moisture sticks are used. Additional work (not reported here) has shown that replacement sticks could be self-manufactured relatively easily. However, ensuring correct calibration/repeatability is an issue in this case.

5. Acknowledgements

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6. References

Anderson HE (1990) Predicting equilibrium moisture content of some foliar forest litter in the northern Rocky Mountains. USDA Forest Service, Intermountain Research Station Research Paper INT-429. (Ogden, UT)

Blackmarr WH (1971) Equilibrium moisture content of common fine fuels found in southeastern forests. USDA Forest Service, Southeastern Forest Experiment Station Research Paper SE-74. (Asheville, NC)

Bradshaw LS, Deeming JE, Burgan RE, Cohen JD (1983) The 1978 National Fire-Danger Rating System: Technical Documentation. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report GTR INT-169. (Ogden, UT)

Britton CM, Countryman CM, Wright HA, Walvekar AG (1973) The effect of humidity, air temperature, and wind speed on fine fuel moisture content. *Fire Technology* **9,** 46–55. doi:10.1007/BF02624840

Burgan RE (1988) 1988 Revisions to the 1978 National Fire-Danger Rating System. USDA Forest Service, Southeastern Forest Experiment Station Research Paper SE-273. (Asheville, NC)

Chandler C, Cheney P, Thomas P, Trabaud L, Williams D (1983) ‘Fire in Forestry - Forest Fire Behaviour and Effects’ (Wiley: New York)

Cohen JD, Deeming JE (1985) The National Fire Danger Rating System: basic equations. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station General Technical Report PSW-82. (Berkeley, CA)

Fischer WC, Hardy CE (1976) Fire-weather observer's handbook. US Department of Agriculture, Agriculture Handbook No. 494. (Washington, DC)

Forest Products Laboratory (1999) Wood handbook - wood as an engineering material. USDA Forest Service, Forest Products Laboratory General Technical Report FPL-GTR-113. (Madison, WI)

Gibos KE (2010) Effect of slope and aspect on litter layer moisture content of Lodgepole pine stands in the eastern slopes of the Rocky Mountains of Alberta. University of Toronto, Master thesis. (Toronto, ON)

Gisborne HT (1933) The wood cylinder method of measuring forest inflammability. *Journal of Forestry* **31,** 673–679.

Haines DA, Frost JS (1978) Weathering effects on fuel moisture sticks: corrections and recommendations. USDA Forest Service, North Central Forest Experiment Station Research Paper NC-154. (St. Paul, MN)

Hardy CC, Hardy CE (2007) Fire danger rating in the United States of America: an evolution since 1916. *International Journal of Wildland Fire* **16,** 217–231. doi:10.1071/WF06076

Kollmann F, Côté WA, Jr., Kuenzi EW, Stamm AJ (1968) Sorption and equilibrium moisture. In 'Principles of Wood Science and Technology. Vol. 1: Solid Wood' (Eds. F Kollmann, WA Côté Jr) pp. 189-195. (Springer: New York)

Norum RA, Miller M (1984) Measuring fuel moisture content in Alaska: standard methods and procedures. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-171. (Fairbanks, Alaska)

NWCG (2009) Interagency wildland fire weather station standards & guidelines. National Wildfire Coordination Group Report PMS-426-3. (Boise, ID)

Pyne SK, Andrews PL, Laven RD (1996) 'Introduction to Wildland Fire' (Wiley: New York)

Van Wagner CE (1972) Equilibrium moisture contents of some fine fuels in eastern Canada. Canadian Forest Service, Petawawa Forest Experiment Station Information Report PS-X-36. (Chalk River, ON)

Van Wagner CE (1987) Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Forestry Technical Report 35. (Ottawa, ON)

Lopes S, Lemos LT, Viegas DX, (2010) Modeling moisture content of dead fine forest fuels common in Central Portugal. In 'Proceedings of the VI International Conference on Forest Fire Research', 15-18 November 2010, Coimbra, Portugal. (Ed. DX Viegas) (CD-ROM) (ADAI: Coimbra, Portugal)

Viegas DX, Lopes SMG, Viegas MT, de Lemos LT (2006) Moisture content of fine forest fuels in the central Portugal (Lousa) for the Period 1996-2004. In 'Proceedings of the V International Conference on Forest Fire Research', 27-30 November 2006, Coimbra, Portugal. (Ed. DX Viegas) (CD-ROM) (Elsevier: Amsterdam)