Predicting tillage outcomes: an energy-based model for soil mechanical fragmentation

Olivier Heller[1,2], Andrea Carminati[2], Sara König[3], John Köstel[1], Hans-Jörg Vogel[3], Ulrich Weller[3], & Thomas Keller[1,4]
[1] Agroscope (Switzerland); [2] ETH Zürich (Switzerland); [3] UFZ (Germany); [4] SLU (Sweden)

Set of equations to predict tillage outcome

Soil tillage is the deliberate mechanical modification of soil structure and represents one of the largest intentional geo-engineering activity on Earth [1,2]. Current approaches to predict tillage outcome remain largely qualitative or implement-specific, limiting the predictive power across soils and operating conditions. Evidence shows that soil water content and intrinsic soil properties dominate fragmentation outcomes [3,4], motivating a physically based, energy-centered tillage equation (Eq. 1) that was parametrized and tested with data from the literature.

$$A_f = f(W, A_i, \theta)$$

Eq. 1: The tillage equation predicts the specific fragment surface area after tillage (A_f) as a function of the tillage energy input (W), the preexisting surface area (A_i) and the gravimetric water content of the soil (θ).

The mechanic energy provided by tillage operations (W) is partitioned into three processes: **soil fragmentation (E)**, **moving soil fragments (S)**, and **plastic deformation of the soil (P)** (Eq. 2).

$$W = E + S + P$$

$$E = \Delta A \cdot \alpha = \Delta A \cdot \sigma_s \cdot \frac{l_{bp}}{2}$$

Eqs. 2, 3: Energy partitioning between different processes. The energy needed to fragment the soil (E) is proportional to the newly created surface area (ΔA). The energy needed to create a specific amount of surface area (α) in turn depends on the bonding strength between soil particles that is governed by the suction stress (σ_s) acting on the particles and the distance need to separate the soil particles (l_{bp}).

The new surface that emerges from tillage (ΔA) is proportional to the **energy available for fragmentation** and the water content dependent bonding strength (α) of the soil particles (Eq. 3)[5]. The share of energy diverted to **plastic deformation** increases with water content dependent soil plasticity (Fig. 1)[6,7]. The energy dissipating from the system by **moving existing soil fragments** increases with increasing fragmentation of the soil (Fig. 1)[4,8].

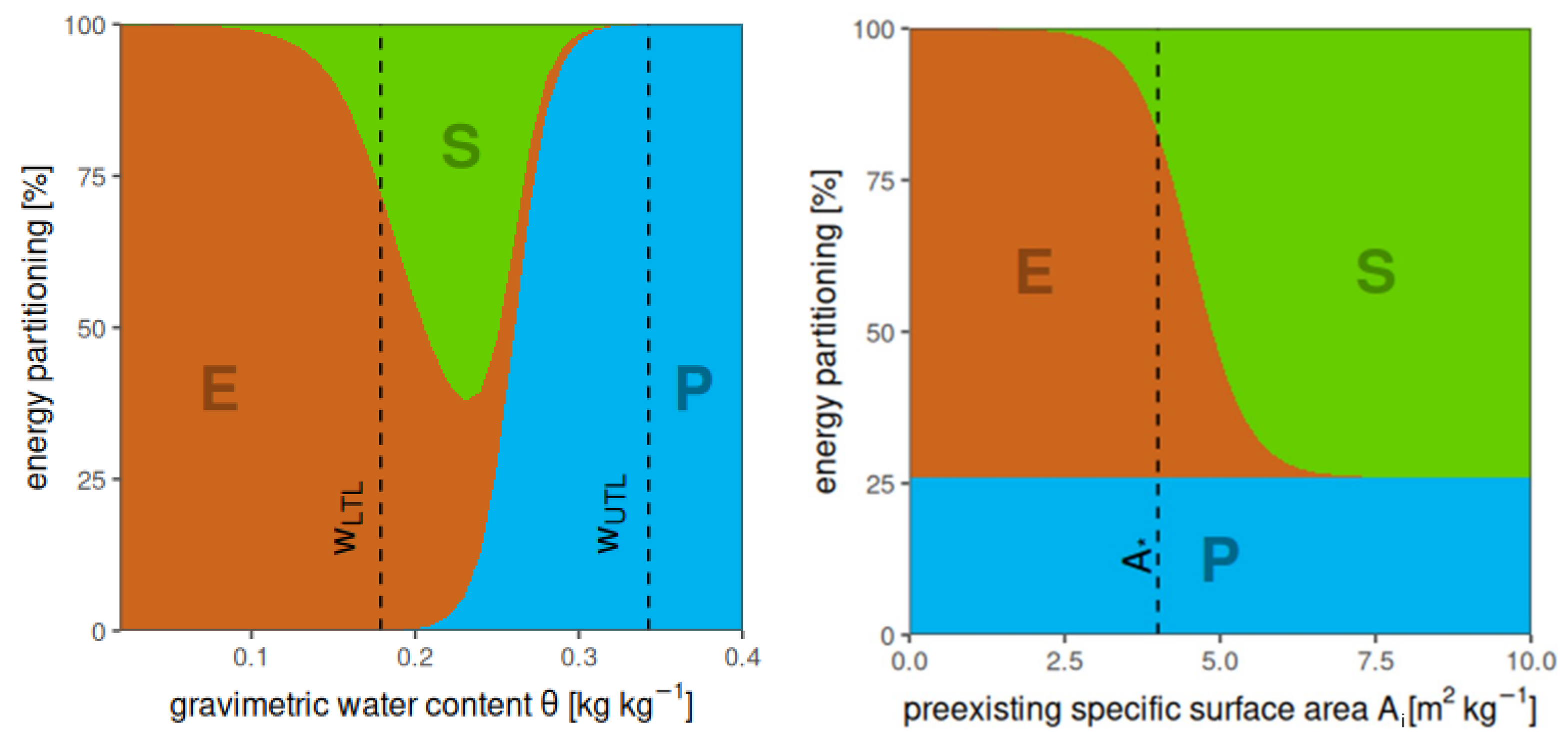

Fig. 1.: The partitiong of tillage energy (W) between different processes depends on the water content (θ) and the current fragmentation of the soil (A_i). w_{LTL} and w_{UTL} represent transition limits of soil plasticity, whereas A_* is the threshold value above which moving of soil fragments is increasingly relevant.

Examples of model application

The parametrized model successfully reproduced well-known patterns. For example, the diminishing effect of subsequent tillage operations (Fig. 2) [4,8] or the contrasting behaviour of soils with different textural classes [9]. Clay soils showed a narrower tillage range and a higher tillage energy needed to produce a good seedbed than Loam soils (Fig. 2).

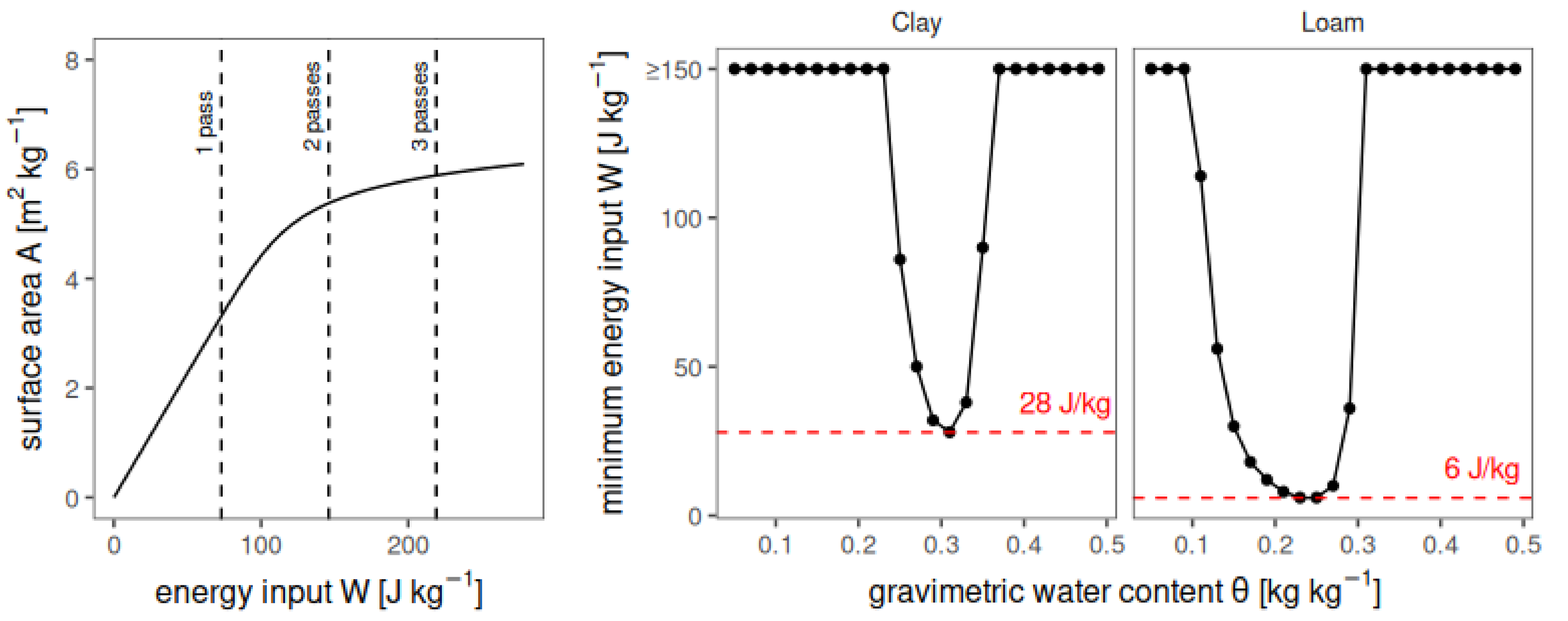

Fig. 2.: The left panel shows the predicted deminishing fragmentation effect of multiple passes with the same implement. The right panel shows the minimum energy required to produce a seedbed with at least 2 $m^2 kg^{-1}$ of specific surface area of two textural classes at different water contents.

Link to soil structure dynamics & water retention

The predicted soil fragment surface area can be transformed to pore size distributions and water retention characteristics (Fig.3) by assuming a Weibull distribution of spherical soil fragments after tillage [10-13]. In a next step, our model could be coupled to models for soil consolidation [14,15] to represent soil structural dynamics in soil–crop models.

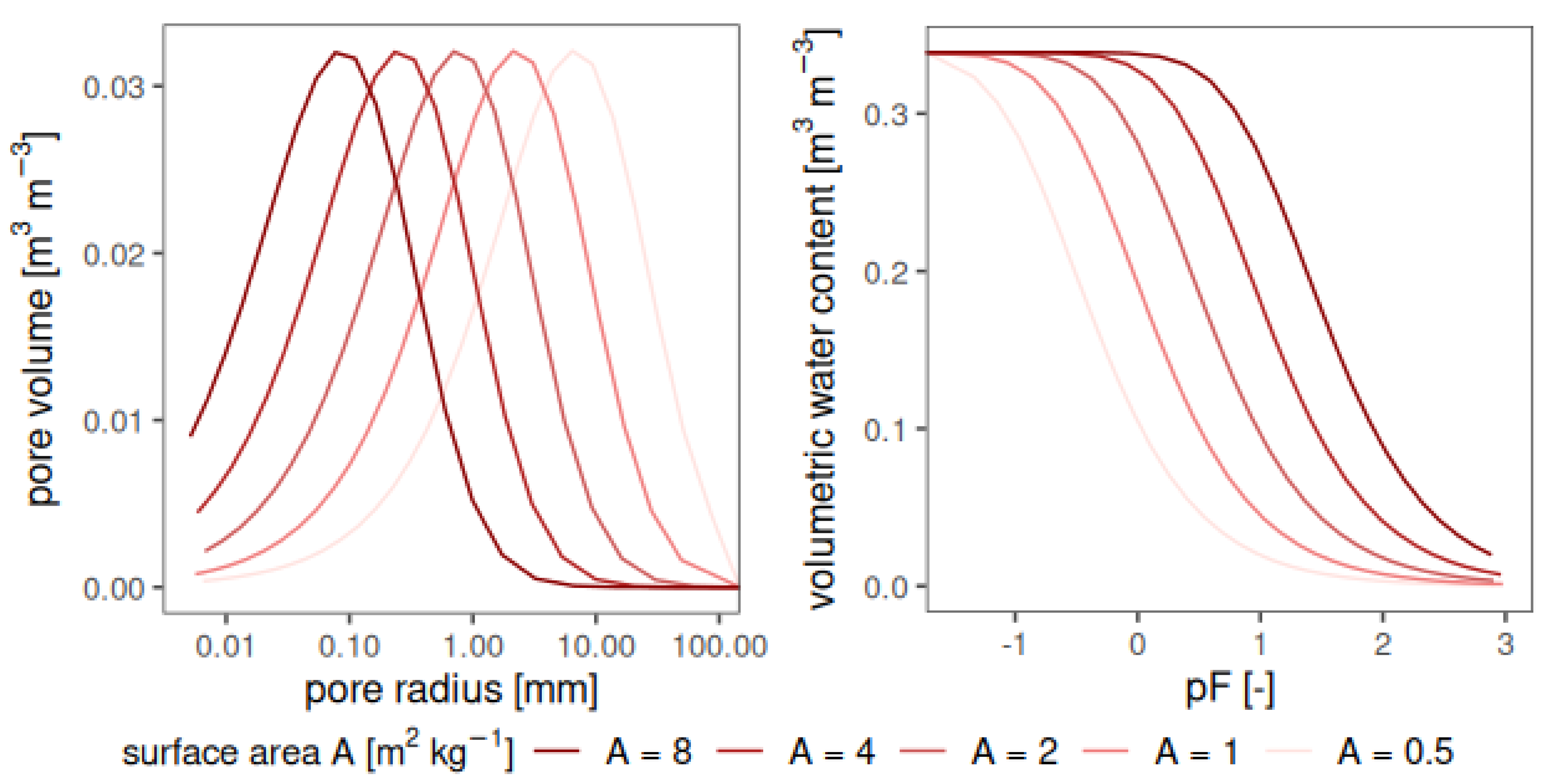

Fig. 3.: The specific surface area of soil fragments can be transformed to tillage pore size distributions with the model of Arya and Paris [13] if assumption about the geometry and size distribution of soil fragments after tillage are made (left panel). The pore size distribution can then be translated into water retention curves of the soil structure produced by tillage.

Summary

A physically based, energy-centred model to predict soil fragmentation by tillage. The model links tillage energy, soil water content, and intrinsic soil properties to fragment size distributions. Parameterised with literature data, it reproduces observed tillage patterns and provides a quantitative basis for coupling tillage with soil structure and hydraulic models.

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