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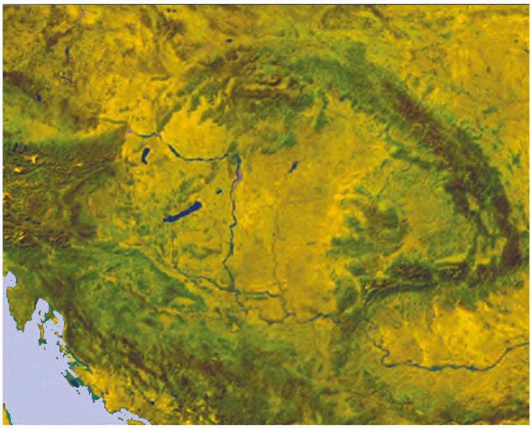

Soil quality, water availability and land use in agricultural areas

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Perspectives of land evaluation of floodplains under conditions of aridification based on the assessment of ecosystem services

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Abstract

Global climate change has discernible impacts on the quality of the landscapes of Hungary. Only a dynamic and spatially differentiated land evaluation methodology can properly reflect these changes. The provision level, rate of transformation and spatial distribution of ecosystem services (ESs) are fundamental properties of landscapes and have to be integral parts of an up-to-date land evaluation. For agricultural land capability assessment soil fertility is a major supporting ES, directly associated with climate change through greenhouse gas emissions and carbon sequestration as regulationg services. Since for Hungary aridification is the most severe consequence of climate change, water-related ESs, such as water retention and storage on and below the surface as well as control of floods, water pollution and soil erosion, are of increasing importance. The productivity of agricultural crops is enhanced by more atmospheric CO_2 but restricted by higher drought susceptibility. The value of floodplain landscapes, i.e. their agroecological, nature conservation, tourism (aesthetic) and other potentials, however, will be increasingly controlled by their water supply, which is characterized by hydrometeorological parameters. Case studies are presented for the estimation of the value of two water-related regulating ESs (water retention and groundwater recharge capacities) in the floodplains of the Kapos and Drava rivers, Southwest Hungary. It is predictable that in the future land evaluation techniques based on the FAO framework will be more dynamic and integrated with the monetary valuation of ESs. The latter task, however, still involves numerous methodological problems to solve.

Keywords: land evaluation, climate change, aridification, ecosystem services, floodwater retention, groundwater recharge, flood reservoirs, floodplains

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Introduction

Conventional land evaluation approaches are either land capability or land suitability surveys. Land capability assessment is meant to measure the overall agroecological potential of a region to produce common cultivated crops and pasture plants (or forestry) without deterioration over a long period of time (Beek, K.J. and Bennema, J. 1972; FAO 1976; Davidson, D.A. 1992). 'Land with the highest capability is expected to be versatile and

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allow intensive use for a reasonably large range of enterprises' (McRae, S.G. and Burnham, C.P. 1981, p. 67). Developed into integral land evaluation (Smit, B. *et al.* 1984), land capability surveys help identify the processes of land degradation (Kertész, Á. and Křeček, J. 2019) and contribute to the foundation of regional development policies. Land suitability assessment is contrived to measure the adaptability of a given area for a specific kind of land use at a given date (FAO 1976).

In Hungary the more than 140-year old 'Goldkrone' system of land evaluation of the Austro-Hungarian Monarchy is still in use – although it will be hopefully soon replaced by the D-*e*-meter system under development (Dér, F. *et al.* 2007; Tóth, G. 2009). The D-*e*-meter is a scientifically based system, which equally considers topography, the water and nutrient availability and complex properties of soils of high spatial but low temporal variability (Pásztor, L. *et al.* 2013) as well as the type of cultivation according to their true significance in land quality. On the scale from 1 to 100, floodplain soils are placed between 30–70 scores in the variety for intensive land use and 20–50 in the extensive variety. In addition, climate (and thus environmental dynamics) is also considered: for the 75 agrometeorological subdivisions of the country by the yields of agricultural crops three kinds of years are distinguished:

- optimal years (when maximum production is achieved),
- 'expected' years (when production is at average level), and
- poor years (when yields are considerable lower).

The system is designed to allow regular updates based on time series information, thus able to incorporate the effect of climate change and the change in agrotechnology as well. Apart from the scientifically sound conceptualisation of soil productivity model, including the effect of climate, soil and management factors (Tóth, G. 2009) other building blocks, such as time series yield and biomass data, validation datasets (case studies, long term field experimental data) and detailed soil maps for the country (Pásztor, L. *et al.* 2017; Tóth, G. *et al.* 2018) enable to develop a productivity map for all agricultural land of the country. However, the evaluation system is only capable of predicting future changes in productivity to a limited extent.

Since the seminal (and much criticized) paper by Costanza, R. *et al.* (1997) on the value of global natural capital and the Millenium Ecosystem Assessment (MEA 2005), ecosystem services (ESs), with emphasis on regulating services, have become a central topic of environmental research. As this concept places the welfare of human society in the focus, this is a novel approach to the assessment of environmental quality. In the most simple definition of the often debated term, ESs are a set of ecosystem functions which are useful to humans (Kremen, C. 2005). According to Costanza, R. and Folke, C. (1997) ESs are 'the benefits human populations derive, directly or indirectly, from ecosystem functions'. Fischer, B. *et al.* (2009) claim that the so-called intermediate services interact to produce final services, which include floodwater retention and freshwater provision. Other pioneers of the ES approach (Potschin-Young, M. *et al.* 2017) question the applicability of the concept of intermediate services. The multiple functions of the landscape (i.e. ESs) are jointly evaluated (Schindler, S. *et al.* 2013, 2014), particularly often for landscapes (like floodplains) where water is the decisive component (e.g. Martin-Ortega, J. *et al.* 2015). However, value judgements on individual services are made difficult by the trade-offs between them (Sanon, S. *et al.* 2012).

The assessment of anticipated changes in the level of provision of ESs is increasingly incorporated in planning (Albert, C. *et al.* 2014, 2016), found essential for achieving landscape sustainability (Wu, J. 2013) and assumed to serve as a measure of effectiveness for rehabilitation works (Alexander, S. *et al.* 2016). Concerning ESs, the elaboration of precise and objective indicators is the most important task in the opinion of many authors (Haines-Young, R. *et al.* 2012). Appropriate methods have to be developed to translate the provision of ESs to a set of parameters. This task can only be accomplished in close cooperation between experts in (landscape) ecology and environmental economics (Thurston, H.W. *et al.* 2009). The valuation procedure, however, should be as simple as possible (Simpson, R.D. 2017).

The EU Biodiversity Strategy to 2020 foresees that Member States map and assess the state of ecosystems and their services on their territories (Zulian, G. *et al.* 2013; Erhard, M. *et al.* 2017; Maes, J. *et al.* 2018; Rendon, P. *et al.* 2019). The starting point was the list of ESs compiled as CICES 4.3 (Common International Classification of Ecosystem Services – Haines-Young, R. and Potschin, M. 2018). In Hungary the National Mapping and Assessment of Ecosystem Services (NÖSZTÉP) was launched in 2017 (Tanács, E. *et al.* 2019). In the first step the research budget only allowed the identification of indicators for a limited number of ESs.

Numerous techniques have been proposed for the assessment and valuation of water-related ESs (Grizzetti, B. *et al.* 2016; Talbot, C.J. *et al.* 2018; Hornung, L.K. *et al.* 2019). Water availability is among the temporally most variable land qualities, which is of crucial significance for agriculture (Lóczy, D. 2000; Falkenmark, M. 2013). Although often evaluated globally (e.g. Gerten, D. *et al.* 2011), it is basically a regional property which cannot simply be described by point-like data (e.g. from soil survey), but the indicators of water availability have to reflect the landscape context, cascading and neighbourhood effects (Xu, H. and Wu, M. 2017; Duarte, G. *et al.* 2018). The water footprint is a concept employed by ecologists in the assessment of sustainability and efficiency of water use in a catchment (Lovarelli, D. *et al.* 2016; Roux, B. *et al.* 2017).

Naturally, flood mitigation is a high-profile ES (Barth, N.-C. and Döll, P. 2016; Opperman, J.J. *et al.* 2017). Permeable floodplain deposits allow floodwater storage and the ability to mitigate floods (Lü, S.B. *et al.* 2012). The substitute cost approach (comparison with alternatives such as man-made reservoirs) is readily applicable to estimate the value of the flood mitigation service provided by wetlands. In the priority list set up on the basis of willingness to pay, flood control is also the most valuable ES of wetlands (Brower, R. *et al.* 1999). In an American case study (Mud Lake, South Dakota) the flood control service of wetlands was valued (based on monetary damages prevented) much higher (at ca. USD 440 per acre, i.e. ca. EUR 1016 ha^{-1} y^{-1}) than water supply (public utility revenues, at USD 94 per acre, i.e. ca. EUR 217 ha^{-1} y^{-1}) and other services (Roberts, L.A. and Leitch, J.A. 1997). In a more recent and more detailed investigation (Cui, L.J. *et al.* 2016) climate regulation makes up 62.0 per cent of the gross value of ultimate ESs provided by the Zhalong wetland (along the Wuyuer River, Heilongjiang province, China), while the value of flood regulation amounts to 33.3 per cent. It was found that German riparian forests avoid damage from a 10-year flood in the value of EUR 4,300 ha^{-1} y^{-1} (Barth, N.-C. and Döll, P. 2016).

The flood control service is closely related to another important service, groundwater replenishment, since with the storage of floodwater in soils and reservoirs promotes its deep percolation (Foster, T. *et al.* 2017). Localized recharge can be more efficient than diffuse recharge (Scanlon, B.R. *et al.* 2002). Key sites of surface water/groundwater interactions (Griebler, C. and Avramov, M. 2015; Salem, A. *et al.* 2020) are Groundwater Dependent Ecosystems (GDEs) like swamps and other wetlands (Eamus, D. *et al.* 2016). The undrained surfaces of the Hungarian Drava Plain mapped within the framework of the Old Drava landscape rehabilitation programme (Trinity Enviro 2018) can be regarded as GDEs *(Figure 1).*

Actual recharge demonstrably reaches the water table, while potential recharge feeds the moisture content of the unsaturated zone but it could potentially also contribute to groundwater in the aquifer (Bergkamp, G. and Cross, K. 2006; Walker, D. *et al.* 2018). Shallow (1 to 1.5 m deep) ponds with infiltration capacities ranging from 1 m d^{-1} to 5 m d^{-1} were found to be suitable for ar-

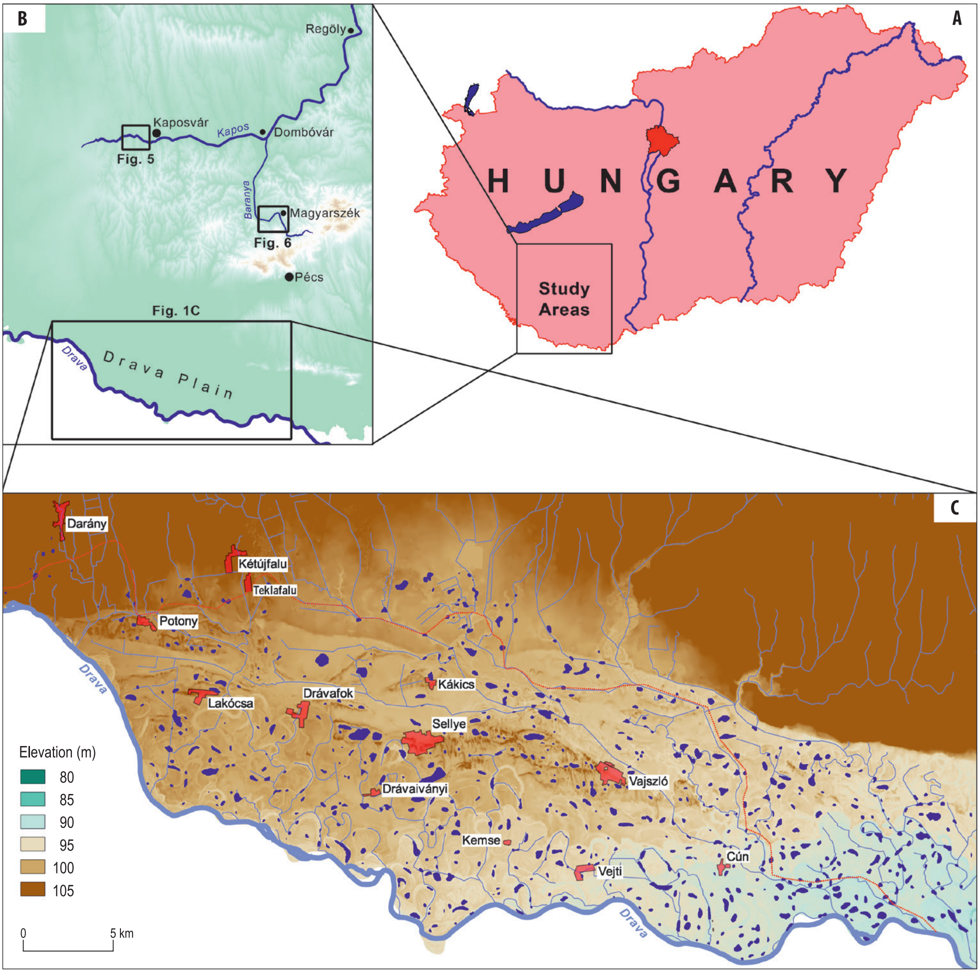

Fig. 1. The study areas in Hungary (1A) and in Southern Transdanubia (1B). 1C = Closed depressions (undrained surfaces), key areas of groundwater recharge, in the landscape rehabilitation area of the Hungarian Drava Plain (drawn by Gyenizse, P. after Trinity Enviro 2018). Pink dots are settlements. Numbers indicate groundwater observation wells in *Table 1.* Red line marks the boundary of the planning area of the Old Drava Programme.

tificial recharge (Jódar-Abellán, A. *et al.* 2017). A study revealed that in the semiarid New Mexico about half the floodwater retained in an experiment infiltrated and recharged groundwater (Valett, H.M. *et al.* 2005). Similar examples are cited from the Mediterranean (Opperman, J.J. *et al.* 2010; Chang, H. and Bonnette, M.R. 2016) and semiarid African regions (Acharya, G. 2000; Acharya, G., and Barbier, E.B. 2000).

The economic value of the groundwater recharge service can also be estimated through the contingent valuation (or willingness to pay) method (Damigos, D. *et al.* 2017) in most cases. In Hungary, however, the general public is not aware of the importance of this service, therefore, a questionnaire survey of this kind probably would not bring reliable results.

The evaluation of nutrient availability is also central in land evaluation systems. The problems in this field can be enlightened with the case of nitrogen. Although its actual quantification is still debated, the nitrogen cycle is one of the critical planetary boundaries (Rockström, J. *et al.* 2009) as it threatens the safe operation of human society. Nitrogen loss takes place to the atmosphere (ammonia and nitrous oxide emissions) and surface and groundwater (nitrate) (van Grinsven, H.J.M. *et al.* 2015). Improper fertilizer and manure application is identified as the most important source of nitrate contamination of groundwater in agricultural regions (see e.g. Diadin, D. *et al.* 2018) and can be reduced by integrating livestock and crop production. The needed planetary N fixation can be derived from demographic trends of the global population, the recommended dietary nitrogen consumption per capita and the efficiency of nitrogen use (de Vries, W. *et al.* 2013).

Global climate change has an impact on the quality of ecosystems and landscapes *(Figure 2).* Higher atmospheric CO_2 concentrations may enhance agroecological potential and improve crop performance, but increased temperature and water scarcity (greater susceptibility to drought) may severely restrict their impact (Gobin, A. 2010; Garofalo, P. *et al.* 2019; Szabó, Sz. *et al.* 2019). Research shows that climate change will particularly negatively affect the yields of crops like cereals (Monaco, E. *et al.* 2014; Bonfante, A. *et al.* 2015; Saab, M.T.A. *et al.* 2019), sugar beet and potatoes (Frutos Cachorro, J. *et al.* 2018). Adaptation can involve modified cropping systems, for instance, sowing winter wheat instead of crops with higher water demand (Debaeke, P. *et al.* 2017). To this extent, crop water requirements and productivity can help make informed decisions across different regions (Gobin, A. *et al.* 2017). The ongoing climate change in Hungary impacts on local water resources (Jankó, F. *et al.* 2018; Jakab, G. *et al.* 2019), particularly drops in groundwater depth, and indirectly on soil and vegetation changes (Farkas, J.Zs. *et al.* 2017; Fehér, Z.Zs. and Rakonczai, J. 2019). In the most severely affected region, on the Danube–Tisza Interfluve, a huge, more than 1,000 mm, moisture deficit accumulated between 1971 and 1985 (Major, P. 1994). Floodplains also show groundwater deficit (for the Drava Plain see e.g. Dezső, J., Lóczy, D. *et al.* 2019).

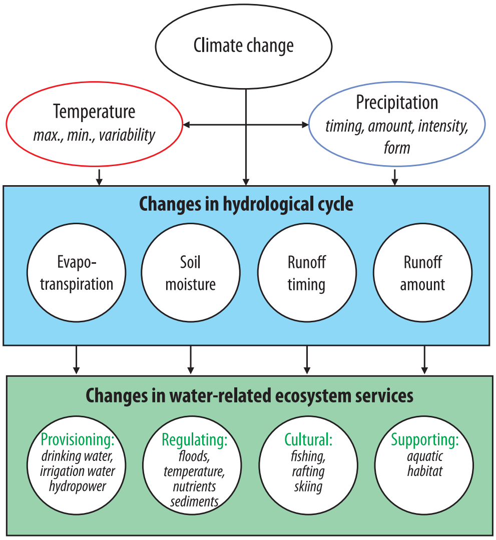

Fig. 2. Cascading effects of climate change on water related ecosystem services (ESs). *Source*: Modified after Chang, H. and Bonnette, M.R. 2016.

The carbon sequestration capacity of soils demonstrates the impact in the opposite direction: that of soils on climate. European soils (particularly peatlands on floodplains) store huge amounts of carbon (73–79 billion tonnes) (Gobin, A. *et al.* 2011). Organic matter content also influences water-holding capacity, thus, soil productivity and environmental quality, and can mitigate the damage caused by droughts and floods.

Agricultural land evaluation has to account for the changeability of input data caused by changing climate (Bonfante, A. *et al.* 2015; Makovníková, J. *et al.* 2019). The productivity of the landscapes varies with the changing circumstances and this will be even more typical in the future (FAO 2017). Although previous systems were primarily based on constant variables, there are several arguments for applying more dynamic techniques in land evaluation (Bonfante, A. *et al.*

2018). Climate change is expected to lead to short-term modifications in the yield potentials of the main economic crops in Europe – although to geographically variable degrees (Supit, I. *et al.* 2010; EEA 2019). While in some regions of northern Europe yield potentials tend to increase (Burkhard, B. *et al.* 2009), in the Mediterranean region major changes in water availability, temperature and radiation significantly reduce potential crop yields (Schils, R. *et al.* 2018) and quality (Bonfante, A. *et al.* 2015, 2017). Along with natural factors, independent from climate change impacts, the vital significance of socio-economic aspects of land system development and land policy in general are often emphasized. It is claimed that social and policy factors can cause a drop of up to 56 per cent in food production (Brown, C. *et al.* 2019).

Methodological approaches: valuation of ESs

Environmental economists have proposed several alternatives for the valuation of ESs (Pascual, U. and Muradian, R. 2010):

- hedonic pricing: if ESs directly influence market prices;
- contingent valuation or willingness to pay: questionnaire survey of people's value perceptions;
- benefit transfer: to infer economic values from the study of similar areas under similar market conditions;
- damage cost avoidance, replacement/substitute cost: damage from lost services, providing substitute(s) for services.

Both benefit transfer and substitute cost seem to be more feasible solutions for the studied water-related ESs in Hungary than the first two which would require a higher level of environmental awareness from the public.

Acharya, G. (2000), and Acharya, G. and Barbier, E.B. (2000) investigated the costs and benefits of development projects, both direct, and indirect, which divert some water away from the floodplain for irrigation in northern Nigeria. The value of replenishing and maintaining the shallow groundwater aquifer was calculated as USD 413 ha^{-1}, the value of groundwater discharge as USD 32.5 per farmer per dry season or USD 62 ha^{-1} and for the entire wetland: USD 13,029 d^{-1}. Since the environmental conditions are starkly different, the transfer of these values to Hungary (see below) is not possible.

In the present paper experimentary monetary evaluations of two interrelated basic ESs are presented for two catchments in Southwest-Hungary: the Drava Plain and the Kapos Valley (see *Figure 1*). Both have to be regarded first approximations. As yet, the reliability of the procedure is equally made doubtful on the grounds of deficiencies in methodology and the inaccuracy of input data.

Examples for the pricing of ecosystem services

Floodwater retention in floodplains

The Water Retention Index (*WRI*) is a useful tool to estimate potential water retention comprehensively (Vandecasteele, I. *et al.* 2018). The WRI is calculated from the equation

$$WRI = (w_v R_v + w_{gw} R_{gw} + w_s R_s + w_{sl} R_{sl} + w_{wb} R_{wb}) \cdot \left(1 - \frac{R_{ss}}{100}\right), \quad (1)$$

where *w*s are the weights to be assigned to each parameter, and *R* are the parameter scores given for retention in vegetation (R_v), groundwater bodies (R_{gw}), soil (R_s), slope (R_{sl}), surface water bodies (R_{wb}), and for soil sealing (R_{ss}).

In the study areas slope inclinations are less than 1.00 per cent and floodplain soils are only sealed in built-up areas. Therefore, the components R_{sl} and R_{ss} could be left out of consideration in the calculations. Moreover, increased water use of forests and grazing lands after floods cannot influence floodwater storage significantly. Thus, in floodwater retention the vegetation effect (R_v) can also be ignored. In contrast, for drought mitigation moisture storage in the vegetation (green water) is an important factor.

In the Drava Plain long-term precipitation is 682 mm y^{-1}, out of which groundwater recharge is 307 mm, actual evapotranspiration (ET) is 190 mm and surface run-off is 185 mm (Salem, A. *et al.* 2019). Actual daily evapotranspiration (ET) in the growing season (April to September) only averaged 1.85 mm d^{-1} for the Drava Plain over the period 2000–2018 (Salem, A. *et al.* 2019). For the Kapos floodplain, however, precipitation (Kaposvár) is 651 mm y^{-1} and yearly ET ranged from 464 to 660 mm in the (slightly overlapping) period 1981–2003 (Bakken, T.H. *et al.* 2006). Consequently, maximum actual ET amounted to ca. 2 mm d^{-1} in the Kapos Valley for the growing season (Lóczy, D. 2013).

It follows from the above that floodwater retention as an ES primarily depends on the amounts of water retained in the soils/deposits and in surface water bodies. The equation that is expected to provide its value is

$$ES_{wr} = w_1C_s + w_2C_{wb}, \qquad (2)$$

where ES_{wr} is the value of the water retention service (HUF ha^{-1}), C_s is the value (substituted cost) of specific water storage in the soil and alluvial deposits (HUF ha^{-1}), C_{wb} is the value of water storage in surface water bodies (HUF ha^{-1}), w_1 and w_2 are weights.

Using nonlinear regression for a sensitivity analysis (Paruolo, P. *et al.* 2013), Vandecasteele, I. *et al.* (2018) established a weighting to both types of water retention, where surface water bodies received exactly double optimized weight (0.24) compared to soils and deposits (0.14). We followed this weighting and arrived at an equation which points to the relative importance of these components:

$$ES_{wr} = (C_s + 2C_{wb})/3 \qquad (3)$$

Water retention in soils and deposits

The capacity of soils for water storage is not apparent but can be very high. It depends on the depth of the vadose zone (to the groundwater table) and soil texture or sediment macroporosity. Groundwater table depth shows strong but fairly regular seasonal dynamics (*Figures 3* and *4*, *Table 1).* This fact supplies a good argument for elaborating a dynamic evaluation of ESs that includes water retention. Extreme yearly ranges (up to > 4 m) occur in some wells, but an average depth of 2.5 m can be accepted for the Drava Plain.

The heterogeneous sequences of floodplain deposits present a great variety of grain sizes from heavy clay and silty fine sand to gravelly coarse sand in the Drava Plain (Dezső, J., Czigány, Sz. *et al.* 2019), while in the Kapos catchment few massive rocks occur and the floodplain is built up of deposits ranging from silt to coarse sand (Lóczy, D. 2013). The macroporosity of alluvial sediments above mean groundwater table depth in the Drava Plain typically ranges from 40 to 50 per cent (sands) between paleochannels and from 55 to 70 per cent in paleochannel clayey deposits (DDVÍZIG 2015; Terraexpert Kft. 2018). Geomorphological mapping in selected representative areas revealed that surfaces with deposits finer than silt make up less than 25 per cent of the total area. Therefore, 50 per cent as an average void ratio was used in the calculations.

For the calculation of below-ground water retention the following equation was used:

$$R_s = (VR \cdot D_{gw})/A, \qquad (4)$$

where R_s is water retention in soil and sediment, VR is mean void ratio of prevailing deposit (fraction), D_{gw} is depth to mean groundwater table (m), A is total catchment area (ha).

The calculated mean storage is 12,600 m^3 ha^{-1} for the Drava Plain. In the Kapos Valley the Regöly embayment had been selected for detailed investigations. Soil profiles were analyzed for maximum (saturated) water capacity and storage capacity (water released gravitationally). The results are the following: 4,039 m^3 ha^{-1} for the areas with chernozem meadow soils, 1,369 m^3 ha^{-1} for the sand areas, 15,916 m^3 ha^{-1} for the meadow soil areas and 2,189 m^3 ha^{-1} for the wetlands (unpublished data by Dezső, J.). The estimated average for the Kapos Valley is 12,800 m^3 ha^{-1}.

Consequently, specific underground floodwater storage potential is roughly equal as regards the Drava and the Kapos floodplains. As a matter of course, the dynamic potential depends on the actual depth of the groundwater table.

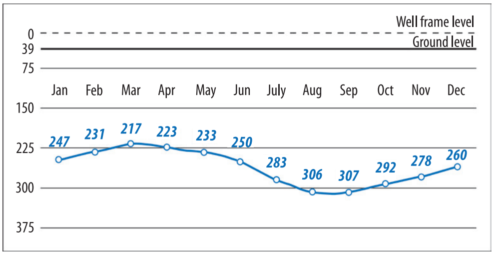

Fig. 3. Long-term monthly groundwater levels at an observation well in the Drava Plain with typical regime, Kemse, 1955–2018. *Source*: DDVÍZIG 2015.

Surface water storage

For the catchment of the Upper Kapos (122,000 ha; ca. 5,500 ha of which is flood-

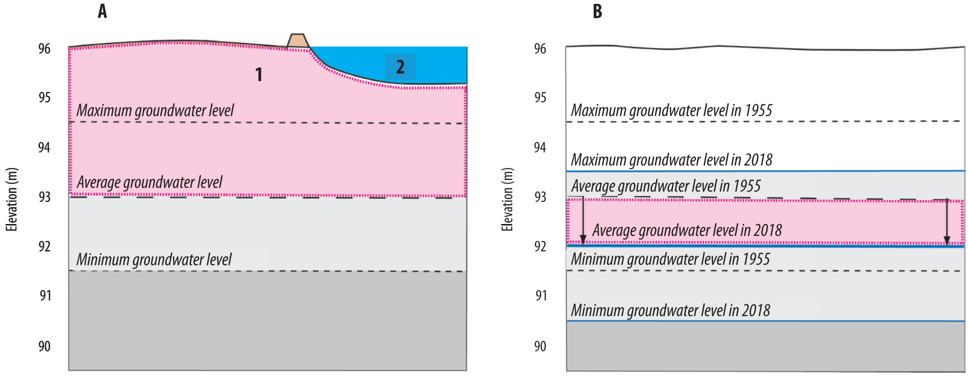

Fig. 4. Scheme of vertical zones considered for water-related ES calculations (by Lóczy, D.). A = Water retention below ground (1), on the surface (2); B = Groundwater recharge. For explanation see text.

*Table 1. Groundwater levels in the observation wells of the Drava Plain**

Well	Distance from Drava, km	Observation period	Groundwater level, m			
			average	maximum	minimum	range
Cún-2	2.7	2015–2017	90.60	91.69	90.01	1.68
Darány	4.4	1979–2016	118.64	120.49	116.37	4.12
Drávafok	5.3	1955–2016	98.68	100.10	97.57	2.53
Drávaiványi	3.9	1975–2016	97.52	99.36	96.11	3.25
Kákics	10.7	1975–2016	97.71	98.92	99.66	2.26
Kemse	3.1	1955–2016	95.28	96.57	91.87	4.70
Kétújfalu	9.2	1955–2016	104.49	106.59	102.01	4.58
Lakócsa	3.9	1975–2016	99.02	100.32	97.75	2.57
Potony	2.9	1955–2016	100.66	103.17	99.17	4.00
Sellye	6.3	1975–2016	98.09	99.24	96.83	2.41
Vajszló	6.5	1951–2016	94.59	96.46	93.63	2.83
Vejti	1.8	1975–2016	94.24	96.67	93.14	3.53

*Compiled by Lóczy, D. 2019. *Data source*: Terraexpert Kft. 2018. For location of observation wells see *Figure 1.*

plain) floodwater reservoir planning in the 1970s calculated with 3,700,000 m^3 retention capacity, but the reservoirs were envisaged to be built mainly along the left-bank tributaries not on the trunk river (Szappanos, F. *et al.* 1976). At Dombóvár (65 river km) the 10 per cent probability flood discharge could be reduced with the help of reservoir storage from 63 m^3 s^{-1} to 47 m^3 s^{-1}. On the trunk river a flood retention reservoir of 3,500,000 m^3 capacity was planned for this purpose but not built. Unfortunately, the financial calculations (HUF 41,200,000, at the present value: ca. HUF 3,500,000,000, based on estimated purchase power parity) are completely outdated now as in the new political and economic system the investment environment is different.

For the Drava Plain, total floodwater storage capacity in the project area of the Old Drava Programme (57,214 ha floodplain) in the surface depressions (see *Figure 1*) is recently estimated at 12 million m^3 (DDVÍZIG 2015). This figure can be accepted as a rough estimate of maximum water retention in surface water bodies. (Although it is doubted to what percentage such depressions can be connected to the Drava River to receive floodwater discharge.)

The application of the substitute cost method was made possible by the fact that repeated inundations of agricultural areas in many valleys of Transdanubia called for the establishment of temporary floodwater-retaining reservoirs (Szappanos, F. *et al.* 1976). The approximate value of natural water retention service is assumed to equal the cost of retention per unit floodplain area achieved by engineering structures (construction expenses of a dam, embankments, a feeder canal and related infrastructure). From the officially published figures (usually obtained from the South Transdanubian Water Management Directorate – DDVÍZIG) of their capacity and investment costs, the approximate expense of retaining 1 m^3 of floodwater can be estimated *(Table 2).*

Assuming that each reservoir collects runoff from the entire catchment above the site of impoundment, the specific cost of water retention is calculated from the equation:

$$C_{swr} = C_{total}/A_{fp}, \tag{5}$$

where C_{swr} is the cost of surface water retention (HUF), C_{total} is total investment cost of the engineering structure (HUF), A_{fp} is floodplain area where floodwater is stored, above the site of river impoundment (ha).

The specific cost derived from this calculation can be regarded equal to a rough estimate of the ES 'flood mitigation through surface retention' in the floodplain. Using equation (3) for the calculation of total floodwater retention potential, and taking irrigation water price at HUF 8 m^{-3} (Kemény, G. *et al.* 2018), the following results are achieved for the Kapos Valley: $ES_{wr} = (12{,}800 \cdot 8 + 2 \cdot 20{,}000 \cdot 8)/3 =$ HUF 140,800 ha^{-1}.

The similar results for the Drava Plain: $ES_{wr} = (12{,}600 \cdot 8 + 2 \cdot 16{,}000 \cdot 8)/3 =$ HUF 118,900 ha^{-1}.

The ES values for the two floodplains of similar character are fairly close to each other.

Groundwater recharge in the Drava floodplain

The pricing of groundwater replenishment service cannot be solved by the substitution cost approach since no technology is known that could supply sufficient amounts of surface water to fill up groundwater reserves.

The aquifer under the Hungarian Drava Plain can be regarded a conditionally independent unit – although it is linked to the right-bank unit in Croatia. The focal areas of groundwater recharge are the closed depression represented in *Figure 1. Table 3* summarizes the (sparse) data available to describe the groundwater situation in the Hungarian Drava Plain.

Extracted unconfined groundwater is primarily used for irrigation (92% in arable farming, 7% in horticulture, 1% in other branches) since its quality is not suitable for drinking water (because of nitrate contamination). Therefore, the price of irrigation water (as a main component of the operation cost of irrigation systems) can be used in the calculation of the ES values.

*Table 2. Parameters of completed and planned flood reservoirs in Southern Transdanubia**

Parameter	Kaposvár (Kapos)[1]	Magyarszék (Baranya Canal)[2]	Potony (Korcsina)	Teklafalu (Korcsina)	Tüskés-puszta	Fekete-víz Stream
Total catchment, ha	312,840	46,200	13,040	13,040	13,400	12,500
Inauguration date	18.05.2014	12.07.2019	planned			
Permanent water stage, m	–	151.0	n.a.	101.5	n.a.	n.a.
Permanent water surface area, ha	0	28	n.a.	52	n.a.	n.a.
Water stage at (100-year) design flood, m	132.8	153.0	102.5	101.5	96.0	89.5
Permanent storage volume, 1,000 m^3	0	410	n.a.	n.a.	n.a.	n.a.
Maximum water surface area during flood, ha	104	54	39/10	52	113	54
Maximum water volume, 1,000 m^3	1,689	1,280	400/370	560	1,200	680
Free capacity, 1,000 m^3	1,689	870	n.a.	0	1,200	680
Mean water depth when filled, m	1.62	n.a.	n.a.	n.a.	n.a.	n.a.
Maximum water depth when filled, m	3.40	n.a.	n.a.	n.a.	n.a.	n.a.
Total cost of implementation, 1,000 HUF	550,000	1,907,000	n.a.	n.a.	1,249,500	1,152,000
Cost of 1 m^3 floodwater retention, HUF	3,256	2,192	n.a.	n.a.	1,041	1,694
Floodplain area above dam, ha	347.5	80.0	65.0	75.0	60.0	38.0
Specific retention capacity, m^3 ha^{-1}	16,240	23,704	n.a.	n.a.	20,000	12,593
Specific cost, 1,000 HUF ha^{-1}	1,583	23,838	n.a.	n.a.	20,825	30,316

*Compiled by Lóczy, D. after DDVÍZIG 2015 and Gscheidt, I. 2017. [1]See *Figure 5*. [2]See *Figure 6*. n.a. = no data.

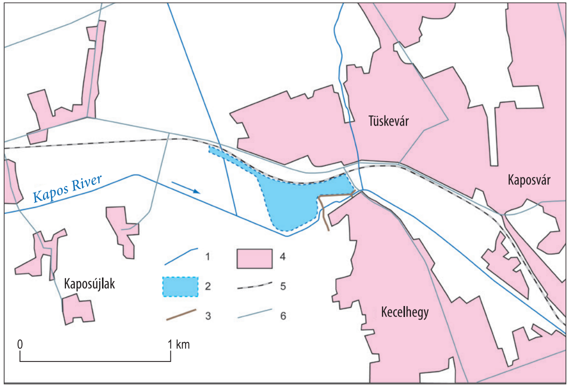

Fig. 5. The flood reservoir on the Kapos at Kaposvár (by Lóczy, D.). 1 = Kapos River and tributary streams; 2 = area inundated during emergency; 3 = dam; 4 = built-up area; 5 = railway; 6 = main public road

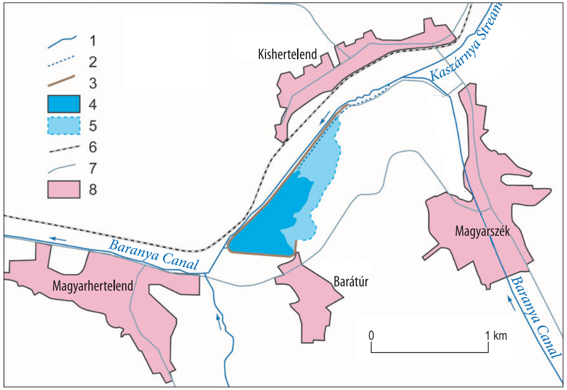

Fig. 6. The flood reservoir on the Baranya Canal at Magyarszék (by Lóczy, D.). 1 = canal, stream; 2 = feeder canal; 3 = dam, embankment; 4 = permanent water surface; 5 = reservoir area inundated during emergency; 6 = railway; 7 = public road; 8 = built-up area

Table 3. Groundwater reserves of the Hungarian Drava Plain, their exploitation** and costs of water utilization****

Parameter	Unit	Value
Total groundwater reserves	m^3	n.a.
Total affected area (planning area)	ha	54,026
Specific groundwater reserve	$m^3\ ha^{-1}$	10,000–15,000
Annual groundwater extraction (based on water rights)	$m^3\ y^{-1}$	2,767,262
Irrigation cost of agricultural land****	HUF $(10\ ha)^{-1}\ y^{-1}$	200,000
Cost of unit extraction****	HUF m^{-3}	300
Worst scenario water price for irrigation water	HUF m^{-3}	40

*The area of the Old Drava Programme. **DDVIZIG 2015, Pécsi HYDROTERV 2015. ***Kemény, G. *et al.* 2018. ****Cost calculations refer to national maximum costs of rotating sprinkler irrigation (at 2017 prices) using subsurface water only. *Source*: Kemény, G. *et al.* 2018. n.a. = no data.

As a very rough estimate, in the short term, the value of the ES of groundwater recharge approximately equals the total extraction cost since the recharge is assumed to compensate for the loss of reserves through human extraction (see *Figure 4*). The starting date of observation of groundwater levels for most of the wells (1955) can be taken as reference and compared to groundwater levels in 2018. The drop of levels between these years indicated in the figure is due to two kinds of human action:

- the construction of hydropower plants and their reservoirs upstream in Croatia, and
- groundwater extraction.

If we calculate with actual groundwater recharge ranging from 0 mm y^{-1} to 360 mm y^{-1}, the average being 241 mm y^{-1} (Salem, A. *et al.* 2020), the annual specific recharge is 0 to 36,000 $m^3\ ha^{-1}$, the average of which is 24,100 $m^3\ ha^{-1}$. Modelling also revealed the spatial distribution of recharge *(Figure 7).*

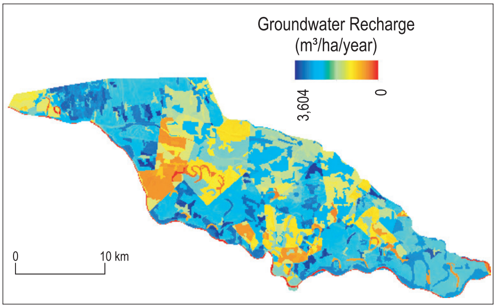

Fig. 7. Spatial distribution of groundwater recharge in the Hungarian Drava Plain (after Salem, A. *et al.* 2020)

The actual price of irrigation water as of 2017 was HUF 8 m^{-3} (Kemény, G. *et al.* 2018). Accordingly, the value of the ES ’groundwater recharge’ can be estimated at HUF 192,800 $ha^{-1}\ y^{-1}$ on the average and HUF 288,000 $ha^{-1}\ y^{-1}$ at maximum. Calculating with the maximum predicted price of HUF 40 m^{-3}, the ES is estimated at HUF 964,000 $ha^{-1}\ y^{-1}$ as an average and 1,440,000 $ha^{-1}\ y^{-1}$ as a maximum. The latter values, however, seem to be unrealistic.

Discussion

There are several factors, processes and complications that may affect the above assumptions on the provision of ecosystem services and complicating their monetary evaluation:

- With warming climate evaporation losses from the open water surfaces of shallow reservoirs and from soil surfaces would reduce surface water retention capacities and should also be considered.
- Natural processes, like the gradual entrenchment of the Drava River, also reduce reserves through ”drawing down” the groundwater table. The groundwater table sank over 48 per cent of the area between 2008–2013 (DDVÍZIG 2015).
- Climate change results in aridification, increased water uptake by vegetation and dropping groundwater table. Summer half-year evapotranspiration is predicted to grow from the present-day maximum of 860 mm to 885–959 mm (Trinity Enviro 2018).

- The groundwater budget shows yearly fluctuations (up to 2.5 m amplitude) with weather conditions.
- The value of floodwater retention and groundwater recharge services cannot be added up, because there is a significant overlap between them.
- Water prices play a decisive role in the calculations.

All these uncertainties also underline the need for a dynamic evaluation. However, at present it is not possible for Hungary because of data shortage. A monitoring network would allow for a dynamic approach to be realised.

How could a land evaluation scheme incorporate ecosystem services valuation? The aims of land evaluation as given in the original Framework (FAO 1976) remain wholly valid; where these refer to the identification of adverse effects and benefits of land uses, there is now greater emphasis on environmental consequences and on wider environmental benefits of ESs (FAO 2007). This way land evaluation could also be made more dynamic, adjusted to changing societal needs.

The incorporation of ESs assessment into the FAO land evaluation system is envisioned in the following way (*Figure 8*):

As a matter of course, it will be possible only if the methodology for the economic valuation of all ecosystem services is elaborated and validated.

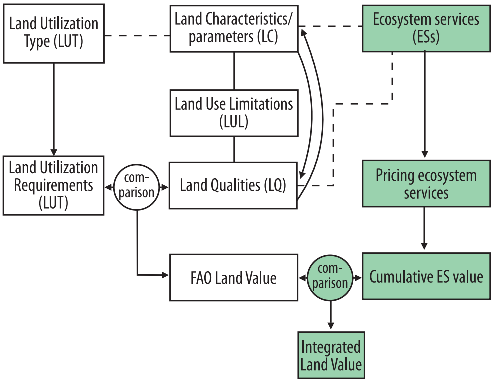

Fig. 8. A possibility of integrating ecosystem services valuation into conventional land evaluation (by Lóczy, D.)

Conclusions

The main goal of land evaluation schemes is to assess the efficiency of landscape functioning at present and under different environmental conditions of the future. The ongoing intensive research directed at ESs provides a new opportunity for the further development of land evaluation systems. In lack of appropriate information and limited knowledge on ecosystem structures and processes the assessment of ecosystem condition is often difficult. With global climate change water-related ESs (including water retention) increasingly come to the foreground. The presently used land evaluation systems are primarily based on static soil parameters which are easy to map and store in a GIS and could be extended to incorporate more dynamic variables that are in tune with the new societal demands. Dynamic and holistic land evaluation is needed, particularly for floodplains where water availability directly or indirectly defines the value of the land to a large extent.

The incorporation of ESs into the FAO evaluation framework seems to be an inevitable task for the future, such as advocated in FAO (2007). We show a clear and practical example of the incorporation of ESs into a LE framework for the Hungarian Drava Plain and the Kapos Valley. At present, however, a wide range of necessary conditions are missing. The price of water is the single decisive factor contributing to the value of water-related ESs.

The integrated assessment will only be possible if most of the important ESs are broken down to indicators by ecologists and expressed in monetary terms by environmental economists. The present study is only meant to be a first step in this direction.

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Application of a topographic pedosequence in the Villány Hills for terroir characterization

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Abstract

Terroir refers to the geographical origin of wines. The landscape factors (topography, parent rock, soil, microbial life, climate, natural vegetation) are coupled with cultural factors (cultivation history and technology, cultivars and rootstock) and all together define a terroir. The physical factors can be well visualized by a slope profile developed into a pedosequence showing the regular configuration of the relevant physical factors for a wine district. In the present study the generalized topographic pedosequence (or catena) and GIS spatial model of the Villány Hills, a historical wine producing region, serves for the spatial representation and characterization of terroir types. A survey of properties of Cabernet Franc grape juice allowed the comparison of 10 vineyards in the Villány Wine District, Southwest Hungary. Five grape juice properties (FAN, NH_3, YAN, density and glucose + fructose content) have been found to have a moderate linear relationship ($0.5 < r^2 < 0.7$) with the Huglin Index (*HI*) and aspect. Aspect, when determined on the basis of angular distance from South (180°), showed a strong correlation ($r^2 > 0.7$) with FAN, NH_3, YAN, sugar and density and moderate correlation with primary amino nitrogen (PAN). HI showed a correlation with three nitrogen related parameters FAN, NH_3, YAN, density and glucose + fructose content. Elevation and slope, however, did not correlate with any of the chemical properties.

Keywords: pedosequence, GIS, terroir, soils, grape juice properties, Huglin Index

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Introduction

The concept of terroir is widely used to explain the unique quality of agricultural products, first of all, of wines. Terroir refers to the geographical origin of wine, the particular interaction of ecosystem factors, including local rocks, topography, climate, soil and others (Biancotti, A. 2003; Vaudour, E. *et al.* 2005; Gladstones, J. 2011; Fraga, H. *et al.* 2014). The biophysical factors are combined with cultural elements (cultivation history, cultivars and rootstocks, viticultural and oenological techniques etc.) to produce a wine of individual character (Seguin, G. 1986; Unwin T. 2012). The usefulness of the terroir concept has been recently supported by GIS tools (Balla, D.Z. *et al.* 2019) whereas its applicability is also confirmed by its rapid spreading from Europe (e.g. Falcetti, M. 1994; Wilson, J. 1998) to all other continents where grapes are grown (Jackson, D. and Lombard, P. 1993; e.g. in Canada: Haynes, S.J. 2000; in South Africa: Wooldridge, J. 2000; in Australia: Halliday, J. 2007). The terroir may be an elusive term sometimes but it provides a very stable background to grapes and wine production. Jackson, D.

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and Lombard, P. (1993) underline that it is mainly the concept of terroir that explains how the appellations of the French wine districts could maintain their quality over centuries. In those districts a huge collective knowledge has accumulated on the interactions between the biophysical environment and the practices applied in vitiviniculture (VVC) which is recognizable in the quality of wine (OIV 2008). The terroir concept also extends to the landscape transformation caused by grapevine cultivation, its literary and fine arts reflections and is used in wine marketing strategies (Vaudour, E. 2001; Jordán, Gy. *et al.* 2005; Szilassi, P. *et al.* 2006).

Although it is impossible to define the ideal climate (temperature, rainfall amount and regime or solar radiation) and the best possible soil for vine growing and wine production, all these complex factors have to be considered in their interactions when terroir is described and assessed (van Leeuwen, C. and Seguin, G. 2006; van Leeuwen 2010; Ferretti, C.G. 2019). The complex interactions explain why the terroir is a typically holistic concept (Malheiro, A.C. *et al.* 2010; Fraga, H. *et al.* 2018).

Topography (slope conditions) is a fundamental component of the terroir as it influences the distribution of parent rock outcrops, some physical and chemical properties of soils and slope deposits, microclimate and natural vegetation (Fraga, H. *et al.* 2014). Elevation, slope angle and aspect are equally influential (Jones, G.V. 2004). Even a 100 m difference in elevation between the top and bottom of the slope may reflect variation within the terroir of the same vineyard plot. Slope inclination and aspect impact on radiation balance, soil erosion, drainage and management (Zsófi, Zs. *et al.* 2011). Where steep slopes require terracing (Šmid Hribar, M. *et al.* 2017), the artificial slope form leads to a fundamental transformation of the terroir.

Among soil parent materials, limestone (the rock building the Villány Hills) has a good nutrient supply to grapes, good drainage but retains moisture under dry weather conditions. There is a single negative effect of carbonates: they cause iron deficiency in grapes (Tagliavini, M. and Rombolà, A.D. 2001). Calcareous soils support excellent blends like Aube in Champagne, Chablis in Burgundy, Pouilly and Sancerre in the Loire Valley and Côtes du Rhône in the Lower Rhône Valley (Wilson, J. 1998).

Physical and chemical soil properties influence grapevine growth and eventually wine quality (Mackenzie, D.E. and Christy, A.G. 2005; Qi, Y.B. *et al.* 2019). Good wines are produced on a wide range of soils (Wang, R. *et al.* 2015; Warmling, M.T. *et al.* 2018) and soil texture may vary from skeletal soils to those with 60 per cent clay (Seguin, G. 1986). Grape juice properties are clearly correlated with plant-available trace elements (Ca, Sr, Ba, Pb and Si) in the soil (Mackenzie, D.E. and Christy, A.G. 2005). If water supply and nitrogen availability are limited, vine vigour, berry weight and yield decline, while sugar content, anthocyanin and tannin concentrations increase in berries (Matthews, M. and Anderson, M. 1988, 1989; Choné, X. *et al.* 2001; Hilbert, G. *et al.* 2003). These 'deficiencies' in soil properties are beneficial to grape quality potential for red wine making. On the other hand, insufficient soil depth and soil compaction hinder moisture storage, root growth and aeration (Jackson, D.I. and Lombard, P.B. 1993). In the Villány Hills the loess mantle compensates for shallow soil depth, but low soil water storage capacity is a risk factor in a region under Mediterranean influence, manifested in increasing heat and water stress (Tardaguila, J. *et al.* 2011). The microbiome in vineyards interacts with the host vine stock, there is a symbiotic relationship between soil and the microbes, which release nutrients from the soil, fix nitrogen, mitigate environmental stresses (drought or toxic contaminants) (Gilbert, J.A. *et al.* 2014). Each wine district (or even terroir) has its own microbial communities which indirectly influence grapes and wine quality (Barata, A. *et al.* 2012).

Topographic and soil variations among terroir units can be best demonstrated on topographic pedosequences. Supplemented with the visualization of GIS data the catena is suitable to indicate microclimate, therefore presenting soils as one of the major components of the terroir (Fraga, H. *et al.* 2014). When soils are considered as integral parts of terroir, then specific terroir units can be more closely related to viticultural data, as well as must properties (Vaudour, E. 2002, 2003; Deloire, A. *et al.* 2005; Bramley, R. and Hamilton, R. 2007).

Climatic factors limit the geographical distribution of grapevine growing and wine vigour and the distribution of white and red wines are also related to topographic, soil and climatic conditions (Fraga, H. *et al.* 2013). The Winkler Index defines the climatic conditions suitable for grapevine cultivation classifying the climate of wine-producing regions based on heat summation or growing degree-days (Winkler, A.J. 1974). Its modified version, the Huglin Index (Huglin, P. 1986), is based on the temperature sum over the temperature threshold of 10 °C for all days from beginning of April to end of September. The Plant Cell Density Index (PCD) is the ratio of reflected infrared (NIR) to red light (R) (PCD = NIR/R) gives a surrogate measure of vine vigour (Hall, A. *et al.* 2002).

Plant protection measures are also site property dependent. Topography influences the occurrence of and damage by some fungi. Interpreting abiotic site factors, new advisory platforms give guidance and end-user information for phytosanitary decision-making including predictions of infection risks for key pathogens identified by satellites and terrestrial radar systems and precisely located by GPS (see e.g. Gabel, B. 2019).

In landscape ecology, the consequences of land use changes are also studied along catenas and for individual terroirs (Jordán, Gy. *et al.* 2005; Lóczy, D. and Nyizsalovszki, R. 2005; Szilassi, P. *et al.* 2006; Novák, T.J. *et al.* 2014).

The paper attempts to prove that the toposequence concept is a correct methodological approach to spatial modelling of the terroir. A soil catena was first explicitly described by Milne, G. (1935) and his colleagues in East Africa in the 1930s (Borden, R.W. *et al.* 2020). The catena became widely adopted in and beyond soil science. Now it is used by ecologists, geomorphologists and hydrologists amongst others. In a modern interpretation the catena indicates spatial patterns of soil and vegetation consistently located in specific topographic positions and is used synonymous with 'toposequence' (Baskan, O. *et al.* 2016). The simplicity, appeal and longevity of the catena concept (Radwanski, S.A. and Ollier, C.D. 1959; Ollier, C.D. *et al.* 1969) makes it suitable for the integration of interdisciplinary research in geomorphology, soil science, hydrology, environmental history and other disciplines related to landscape studies.

Recently, several terroirs have been identified in the Villány Wine District: Jammertal, Csillag-völgy (*Sterntal*), Remete (*Einsiedler*), Ördög-árok (*Teufelsgraben*), Kopár. The differences between their natural potentials for grapes cultivation largely depend on their position on the toposequence.

The objectives of the present study were to interpret a typical pedosequence revealing a regular geographical pattern of environmental factors (slope parameters, parent material, soils, microclimate, natural vegetation etc.) for the characterization of the terroir. The Villány Hills, selected for investigation, is a well-defined wine district with a relatively simple geology and geomorphology. Therefore, a single typical topo-pedosequence is able to represent the configuration of geographical terroir factors (Switoniak, M. *et al.* 2017; Czigány, Sz. *et al.* 2018).

Although a single parameter of grape juice or wine cannot comprehensively characterize a terroir, we attempt to reveal variations in nutrition properties of grapes from different vineyards of the Villány Wine District. In 2018 and 2019 the local producers of Cabernet Franc, a variety getting increasingly popular in the region, agreed to harvest grapes at the same date and to use the same technology in wine making. The objective of the present paper is to compare the impact of the physical environment on wines from 10 plots in different locations and to draw correlations between the topographic parameters of vineyards and the nutritional properties of their produces. The paper is *not* aimed at establishing a ranking among the studied terroirs.

Study areas

Location

The Villány Wine District extends over various altitudinal regions of the Villány Hills, SW-Hungary *(Figure 1)*, stretching ca. 30 km in an east-western direction from the village of Hegyszentmárton to the small town of Villány *(Figure 2)*.

Lithology and topography

The Villány Hills form the southernmost hill range in Hungary. The hills are predominantly built up of Triassic, Jurassic and Cretaceous limestones and dolomites, covered by Pleistocene loess at lower elevations (Lovász, Gy. and Wein, Gy. 1974; Lovász, Gy. 1977). In summits of the eastern and western ends limestone and dolomite commonly outcrop (Wein, Gy. 1967). The range constitutes of uplifted and imbricated horsts. The sedimentary rocks that form the bulk of the range were thrust on each other in a thrust fault style forming blocks or 'shingles' (Dezső, J. *et al.* 2004; Sebe, K. 2017). The blocks are bordered by fault lines that dip to the West (Lovász, Gy. 1977). The blocks are tilted to the West or Northwest, in the case of the Csarnóta block to the South and in the Szársomlyó block to the North. Additional Mesozoic horsts and outcrops are found in the southern foreground of the range including the Siklós Castle Hill, the Beremend Hill and the Kistapolca Hill (Czigány, Sz. 1997). The summit regions are covered by shallow loess-like sediments and soils in a discontinuous fashion, while limestone caverns are filled in by Pliocene red clay (Lovász, Gy. 1973).

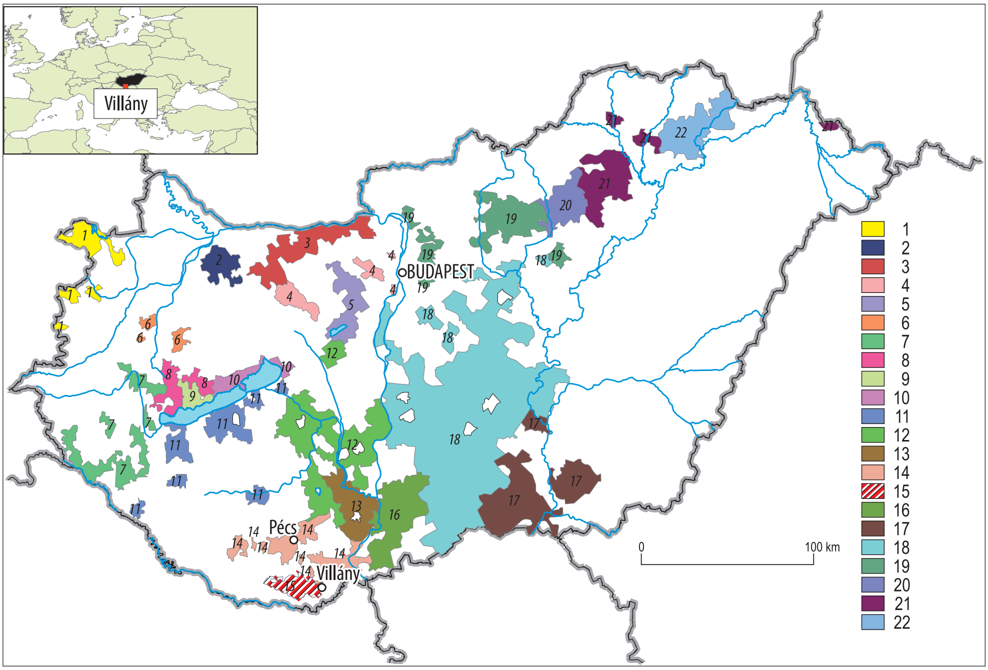

Fig. 1. Location of the Villány Wine District (no 15) in Hungary. Wine districts: 1 = Sopron; 2 = Pannonhalma; 3 = Neszmély; 4 = Mór; 5 = Etyek-Buda; 6= Somló; 7 = Zala; 8 = Balaton Highland; 9 = Badacsony; 10 = Balatonfüred-Csopak; 11 = Balatonboglár; 12 = Tolna; 13 = Szekszárd; 14 = Pécs; *15 = Villány*; 16 = Hajós-Baja; 17 = Csongrád; 18 = Kunság; 19 = Mátra; 20 = Eger; 21 = Bükk; 22 = Tokaj

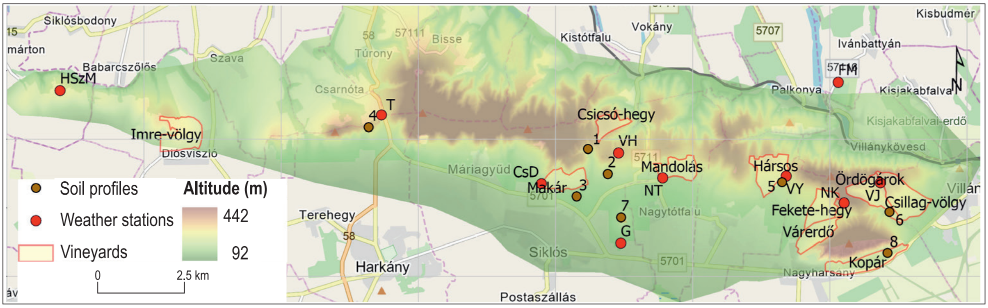

Fig. 2. Map of the Villány Wine District with locations of the studied vineyards, soil profiles and meteorological stations. Soil profiles: 1 = Melegmál; 2 = Városihegy-dűlő; 3 = Zuhánya-dűlő; 4 = Kopasz Hill, Csarnóta; 5 = Fekete-hegy, Vylyan vineyard; 6 = Ördögárok; 7 = Göntér; 8 = Kopár. Meteorological stations: HSzM = Hegyszentmárton; T = Túrony; CsD = Csukma-dűlő; VH = Városi-hegy; NT = Nagytótfalu; G = Göntér; VY = Vylyan winery; FM = Fáni-major (not used for meteorological analysis); NK = Nagyharsány-Konkoly; VJ = Villány-Jammertal (Background: OpenStreet Map/ArcGIS, 5-meter DEM)

The highest point of the westernmost block is 268 m (Kopasz Hill). Here the limestone is extensively found on the surface and exposed in the Csarnóta Limestone Quarry. The average height of the block to the East (Csukma block) is around 340 m with Tenkes Hill (408 m), which is the second highest peak in the entire range. The summit elevation then decreases to about 240 m in the central, lowest part of the range (Város Hill block) North of the town of Siklós. Here, in this block, the consolidated bedrocks (limestones and dolomites) are only exposed in road cuts, gullies and ravines. To the East the range again gains height (Fekete Hill, 358 m). The highest point of the hills is Szársomlyó (442 m). The Ördögszántás ('Devil's ploughfield') is a lapiés field carved on the faces of the north-dipping limestone strata on the southern slopes of Szársomlyó Hill. Here loess only covers the northern and the southern foothills (Lovász, Gy. and Wein, Gy. 1974; Czigány, Sz. 1998).

Vegetation and land use

There is a pronounced mesoclimatic and vegetational contrast between the southern and northern slopes. The loess-covered northern slopes and summit regions are dominated by silver lime (*Tilia tomentosa*), hornbeam (*Carpinus betulus*), pedunculate oak (*Quercus robur*), Turkey oak (*Quercus cerris*) and locally by beech (*Fagus sylvatica*). The natural vegetation on the southern slopes is a xerothermic wooded grassland on karst spotted with sparse rocky grasslands (Borhidi, A. and Dénes, A. 1997). A typical Mediterranean karstic steppe is found on the limestone surface of the southern slopes of the Szársomlyó Hill, with downy oak (*Quercus pubescens*), South European flowering/manna ash (*Fraxinus ornus*) and invasive tree of heaven (*Ailanthus altissima*). The loess-covered southern hillslopes are used as vineyards (Tengler, T. 1997). The dirt roads leading to the vineyards have developed into sunken lanes which built alluvial fans of loess deposits at the base of slope (Czigány, Sz. 1997; Czigány, Sz. and Nagyváradi, L. 2000).

Climate

The region is located in the semi-humid temperate zone with hot summers (Lovász, Gy. 1977; Kottek, M. *et al.* 2006), ustic soil moisture and mesic temperature regimes according to the USDA's Soil Taxonomy. Mediterranean and arid continental influences are also present. Mean annual temperature is 10.8 °C (for 1971–2000, recently 12.0 to 13.2 °C) and average temperature of the coldest month (January) is -0.5 °C, while the warmest month is July with mean temperature of 22.5 °C. The average annual precipitation total is around 680 mm in the region. The 30-year average value is 661 mm for the town of Siklós, 684 mm for Nagytótfalu, 694 mm for Villány, and 701 mm for the town of Harkány (1971–2000 data, Hungarian Meteorological Service, OMSz). Based on the 1981 to 2010 meteorological record, February is the driest (32 mm), while the highest precipitation (83 mm) is recorded in June (Bötkös, T. 2006).

Methods

Soil sampling

Four representative soil profiles were excavated along the southern slopes of the Villány Hills from the ridge to the southern foothill position and further four profiles were used for verification. Profiles were manually excavated to a depth of about 120 cm or to the depth of the parent material. Profile locations were selected according to slope position, parent material and land use. Soil profiles were described and classified: master and diagnostic horizons were determined according to the WRB (World Reference Base for Soil Resources; Guidelines for soil description by FAO 2006; IUSS Working Group 2015;). Munsell color, field moisture conditions and soil structure of each horizon were determined in the field.

Disturbed soil samples were then taken from the centre of each horizon and were analysed in the laboratories of University of Pécs and University of Debrecen for particle size distribution. Particle size distribution was determined using a MasterSizer 3000 (Malvern Inc. Malvern, United Kingdom) particle size analyser, and combined wet sieving (2.0–0.2 mm fractions) and the pipette method (<0.2 mm fractions) (Pansu, M. and Gatheyrou, J. 2006).

Spatial visualization of climate data

Climate data were obtained from 9 meteorological stations, maintained by the Tenkes Wine Region Management Corporation (see *Figure 2).* Sensors of the stations were manufactured by the Boreas Ltd. (Érd, Hungary). Weather data included air temperature, precipitation, insolation, relative humidity, wind speed and wind direction. Only the year 2013 was devoid of hiatus, hence it was selected for the calculation of the Huglin Index (*HI*), used for the evaluation of climatic influences on terroir properties. Eventually, HI is a method for classifying the climate of wine growing regions based on heat summation of growing degree-days (Huglin, P. 1986). The index assumes that growth of the grape plant begins when daily mean temperature reaches 10 °C in the spring and was calculated for the days when the 5-day moving average of daily mean temperatures reached a minimum of 10 °C (growing season) with the following equation:

$$HI = \frac{T_{min}+T_{max}-20}{2}, \qquad (1)$$

where T_{min} and T_{max} are the daily minimum and maximum temperatures during the growing season, respectively.

All point weather data were then interpolated and weighted according to the 2013 raster based insolation GIS database of the area. Correlation between the incoming solar radiation of the nine weather stations and HI was calculated by fitting a linear trend line on the corresponding data in a form of $y = \mathrm{a}x + \mathrm{b}$. (The actual equation is $y = 0.0033x - 1{,}813.2$.) Derived temperature data were further weighted as a function of vertical elevation gradient at a rate of 0.65 °C decrease of temperature for each 100 m elevation increment. All raster calculations were done in ArcGIS Pro software environment.

Vitivinicultural data and statistical analyses

Ten vineyards were selected for verification purposes of the terroir-catena approach model (see *Figure 2).* Tartaric acid, malic acid, pH, primary amino nitrogen (PAN), free amino nitrogen (FAN), NH_3 content, yeast assimilable nitrogen (YAN), density, °Brix and sugar content (glucose + fructose) of Cabernet Franc grape juice, obtained from vintners, were used for model verification. Correlation coefficients (r^2) using linear relationships were then determined between the vitivinicultural (VVC) properties and the factors influencing terroir properties (HI, elevation, slope inclination and aspect). Anova statistics and cluster analysis were run using PAST 2.0 software for the must properties of each vineyard.

Results and discussion

Soil genesis and systematic position

The investigated soil profiles exhibit a high diversity of soils. The pedosequence represents a typical series of soils starting from the summit, covered by loess, overlying the weathering products of limestone. From the steepest slope sections the loess cover has been eroded or has not even accumulated. Therefore, the (weathering residue of) limestone outcrops. These are mostly protected areas, preserving the native vegetation cover, with farming activities precluded *(Figure 3, Table 1).*

Profile 1 (45°52′45.19″N, 18°18′57.67″E) was excavated in the Meleg-mál vineyard, located in a relatively gently sloping summit position covered by loess deposits (soil parent material). The upper section and the most convex segment of the slope is covered by *Endocalcaric Cambisol* (Siltic, Ochric) (IUSS Working Group 2015) (*Figure 3*, a; *Table 1*, Profile 1). The texture in the entire soil profile is typical of soils formed on loess deposits, i.e. mainly silty loam.

Profile 2 (45°53′06.2″N, 18°13′53.7″E) was excavated South of the village of Csarnóta, East

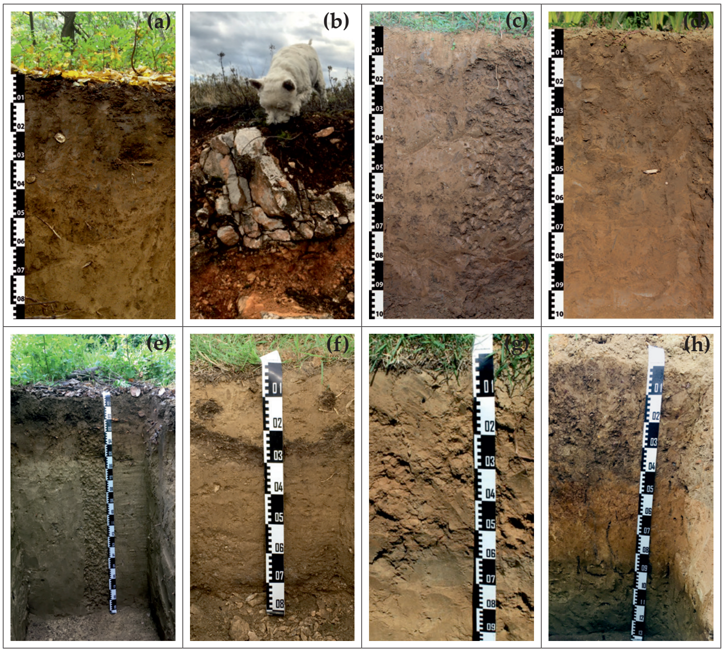

Fig. 3. Representation of the four profiles used for catena characterization (upper photos): Meleg-mál (a); Kopasz Hill, Csarnóta (b); Városi-hegy vineyard (c); Zuhánya vineyard (d); and the four profiles used for verification (lower photos): Ördög-árok (e); Göntér (f); Fekete-hegy, Vylyan winery (g); Kopár (h)

Table 1. Description of the eight studied soil profiles

Name of the profile	Horizon	Depth, cm	Percentage share fraction, %			Diagnostic soil type (WRB) and coordinates	Textural class
			sand	silt	clay		
1. Meleg-mál	Ah	0–10	11.3	79.9	8.8	Endocalcaric Cambisol (Siltic, Ochric) 45 52′45.19″N, 18 18′57.67″E	SL
	Bw	10–40	10.7	64.8	24.5		SL
	BC	40–65	11.1	71.4	17.5		SL
	C	65–(80)	11.5	80.0	8.5		SL
2. Csarnóta	Ah	0–15	28.6	66.3	5.1	Somerirendzic Leptosol (Humic, Siltic) 45 52′45.19″N, 18 18′57.67″E	SL
	ABw	15-28	33.7	61.4	4.9		SL
	CR	42–65	33.9	61.1	5.0		SL
3. Városi-hegy	Ap	0-20	33.1	63.0	3.9	Haplic Luvisol (Aric, Cutanic, Humic, Pantosiltic, Bathycalcic) 45°52′23.6′′N, 18°19′11.2′′E	SL
	Ah	20-40	46.0	51.1	2.9		SL
	Ah2	40–55	32.0	64.2	3.8		SL
	Bt	55–165	16.7	66.2	4.1		SL
	Bw	165–200	23.8	71.6	4.6		L
	C	200–(220)	24.4	71.2	4.4		SL
4. Zuhánya	Ap	0–20	11.4	83.7	4.9	Calcaric Luvisol (Aric, Cutanic, Humic, Pantosiltic) 45 52′05.6″ N, 18 18′34.4″, E	SL
	Ah	20–60	21.0	75.0	4.0		SL
	Bt	60–140	17.7	77.1	5.2		SL
	C	140–	24.4	71.2	4.4		SL
5. Ördög-árok	A(h)	0–20	13.7	57.8	28.5	Cambic Calcisol (Epiloamic, Endosiltic, Humic) 45 51′52″ N, 18 25′27″E	SCL
	Bw	20–50	12.2	58.6	29.2		SCL
	Ck1	50–70	20.3	59.8	19.9		SL
	Ck2	70–190	19.4	60.6	19.9		SL
6. Vylyan	Ap	0–20	13.7	57.5	28.8	Endocalcic Luvisol (Aric, Ochric, Cutanic, Anoloamic, Endosiltic) 45 52′23.32″N, 18 23′12.36″E	SCL
	Bt	20–55	11.1	59.0	29.9		SCL
	Ab	55–75	11.2	59.0	29.8		SCL
	Ck	75–150	12.5	61.0	26.5		SCL
7. Göntér	Ck	0–7(20)	21.0	57.4	21.6	Endoskeletic Calcisol (Anosiltic, Endoloamic, Ochric) 45 51′41.61″N, 18 19′33.57″E	SL
	A/Cbk	20–35	36.2	47.6	16.2		L
	Ck2	35–55	17.6	59.8	22.6		SL
	C/Rk	55–85	33.5	44.4	22.1		L
	R	85–	–	–	–		–
8. Kopár	Apk	0–15	13.5	56.0	30.5	Cambic Calcisol (Epiloamic, Endosiltic, Aric, Anohypocalcic, Epiochric) 45 51′8.48″N. 18 25′19.36″E	SCL
	A/Ck	15–55	13.0	56.2	30.8		SCL
	Ck	55–190	12.8	62.4	24.8		SL

of Kopasz Hill, on a karstic surface with limestone blocks on surface, at the edge of a quarry, with the surface above having an inclination of 3° at an elevation of 191 m (*Figure 3*, b; *Table 1*, Profile 2). Due to the shallow topsoil, the soil is classified as *Somerirendzic Leptosol* (Humic, Siltic). Particle size distribution is dominated by silt and partly by clays, classified as silt loam. Highest clay contents are observed in the B_w and BC horizons. Profile 2 represents a soil developed on limestone outcrops (qualifier *Rendzic*) and its clayey weathering products, containing sand and silt fraction with silty loam texture throughout. The most important feature of the profiles is the presence of coarse fragments in the subsoil and the shallow, carbonate-rich, humic surface epipedon. Soil depth in the vicinity of the profile is highly variable, but generally less than 55 cm.

Profile 3 (45°52′23.6″N; 18°19′11.2″E) was excavated in the Városi-hegy in a midslope position with SSE aspect and an inclination of 5° at an elevation of 154 m (*Figure 3*, c; *Table 1*, Profile 3). In terms of land use this had been a vineyard until 2001, when it was left fallow. The soil is classified as Haplic Luvisol (Aric, Cutanic, Humic, Pantosiltic, Protocalcic) with silt loam texture. Clay accumulation characterizes the profile below the depth of 40 cm. It is a *Haplic Luvisol (Aric, Cutanic, Humic, Pantosiltic, Bathycalcic)* developed predominantly on colluvic material and reworked loess-paleosol deposits. The profile was excavated in an abandoned vineyard where cultivation ceased in 2002. The profile indicates a certain degree of leaching and clay translocation, texture is dominated by the silt fraction (Pantosiltic). Since this part of the Villány Hills has been cultivated for the longest time, redeposited sediments accumulated by both natural slope processes and viticulture practiced since Roman times (Aric).

Profile 4 (45°52′05.6″N; 18°18′34.4″E) was excavated in an actively cultivated vineyard on a very gentle slope inclination of 3° at an elevation of 124 m in foothill position (*Figure 3*, d; *Table 1*, Profile 4). Classified as a *Calcaric Luvisol* (Aric, Cutanic, Humic, Pantosiltic) similar to Profile 3, it represents a relatively young soil developed as a consequence of *colluvic* accumulation (supplementary qualifier *Colluvic*), transported from upslope by erosion since the area was arable land in the past (Aric) (Lovász, Gy. 1977; Tengler, T. 1997; Czigány, Sz. 1998). The texture of slope deposits is mainly silt (*Pantosiltic*). The *colluvic material* has a humic character in the entire profile, probably due to the erosion of topsoil further upslope.

Two profiles out of the four soil profiles used for verification purposes are located in foothill position: Kopár and Ördög-árok. Yet they have a relatively shallow soil of about 50 cm, underlain by loess deposits (see *Table 1*). For the Kopár, the actual topsoil had a depth of only 5 to 15 cm. The soil profile in the Vylyan vineyard (*Table 1*, Profile 6) is in mid-slope position with a soil depth of 55 cm and with a buried topsoil between 55 and 75 cm. Oddly, the Göntér profile (*Table 1*, Profile 7), despite its plateau (summit) position exposed a heavily ploughed and relatively shallow soil with limestone boulders already occurring at a depth of 55 cm.

Characterization of the pedosequence

The typical pedosequence of the Villány Hills *(Figure 4)* was generated by the parent materials (limestone, loess and colluvium), topography and subsequently modified by agricultural activities and natural erosional processes. With the exception of Profile 1, the properties of all analysed profiles, were strongly influenced by human-induced erosion. (Profile 1 is a fairly natural profile on a very gentle slope of the plateau. Erosional processes did not remove the loess cover completely, only inhibited deeper soil development and organic carbon accumulation. Profile 2 is located in the erosional section of the investigated slope. The shallow soils here are discontinuous and scattered, altering with rock outcrops without any soil cover. Formerly, Profile 2 may have also been covered by loess, but we may also deduce that dust deposition itself was not possible here due to steep slopes, and soils have always developed on weathering products of limestone (Leptosols).

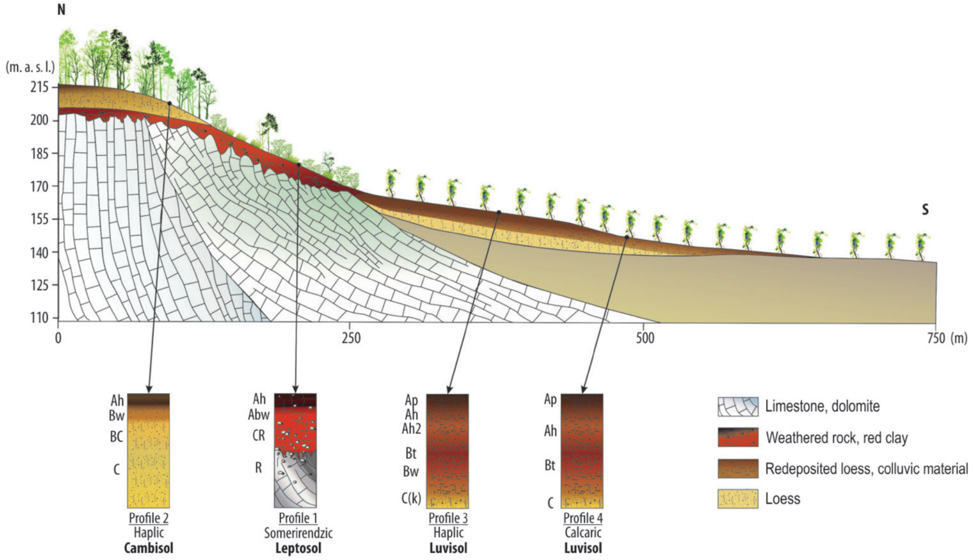

Fig. 4. Typical topographic pedosequence of the southern slopes of the Villány Hills (by Czigány, Sz. and Novák, T.J.)

Nevertheless, the presence of former and existing Cambic B_w or even Argic B_t horizons is also possible in the case of thicker weathered material, which could be eroded later as a consequence of human influence (deforestation, grazing etc.). Today Profile 2 is heavily eroded: the shallow topsoil may have been truncated. Intense derasional processes must have occurred here in the past, probably due to land use (quarrying, vineyards), but also for natural reasons (steep slope, lack of dense forest cover). However, lately, over the past decades, no tillage has been practiced.

Soils developed on redeposited colluvial deposits dominate the middle and lower sections of slopes (profiles 3 and 4). Currently, slope processes have been restrained by grass vegetation and no-till viticulture, which also leads to organic matter enrichment. In Profile 4 humus accumulation was detected in the pedon – probably due to manuring and mineral fertilization.

The impact of erosion, horizontal translocation and re-deposition according to slope position is reflected in the systematic sequence of the described soils. Profile 1 has been markedly eroded and truncated. Therefore, profile development is poor and it was classified as a Cambisol. Profile 2 with shallow Humic and Calcic horizons, but a significant amount of coarse limestone fragments, was classified as Leptosol. Profiles 3 and 4 are both colluvial soils classified as Luvisols. Marked human impact is clearly visible in Profiles 2, 3 and 4, as their upper sections have been eroded, redeposited and transformed into material with coarse granular structure.

Spatial pattern of climate data

The weighted and interpolated map of the HI indicated the marked insolation and temperature variations as a function of slope aspect and elevation. Although elevation differences are limited and relief is subdued in the Villány Hills, topography still has a profound impact on temperature distribution.

Due to the globally observed increasing temperatures heat indices have regularly exceeded the preferred range of the commonly grown grape varieties of the Villány region over the past years. That was especially true for the relatively warm year of 2013. HIs of 2013 commonly exceeded 21 °C-day on the southern slopes of the Villány Hills. These are markedly higher than the preference of the commonly grown grape varieties of the Villány region *(Figure 5).*

Mean HIs ranged between 1,749 and 2,060 degree-hours for the studied 10 vineyards *(Table 2).* The lowest value was found for the Várerdő vineyard located in the north-eastern foreground of the Szársomlyó Hill. The highest value was found in the Kopár vineyard in the south-eastern footslopes of the Szársomlyó. Vineyards in plateau positions, despite their somewhat higher altitude, still had high HIs around 2,000 degree-hours. Csicsó-hegy was the only exception among the vineyards in plateau positions, with a mean HI of 1,896.

Spatial distribution of topographic parameters

Aspect played an important role on the selection of the studied vineyards. Aspect shows a great variability among the studied vineyards. The Várerdő vineyard had the theoretically less favoured WNW average aspect, with a range from SE to NNW *(Table 3).* The Mandolás, Makár, Hársos, Csicsó-hegy and Kopár vineyards face almost exactly to the South, however, the first four of them essentially found in plateau position with relatively gentle slopes.

Table 2. Spatial statistics of the Huglin Index for the ten studied vineyards

Vineyard	Mean	STD	Median
Hársos	1,983.83	84.87	1,987
Várerdő	1,749.81	60.97	1,716
Fekete-hegy	1,966.20	103.22	1,978
Kopár	2,060.50	51.34	2,093
Csillag-völgy	1,959.49	83.00	1,963
Ördög-árok	1,943.83	158.58	1,994
Imre-völgy	1,949.16	100.49	1,953
Mandolás	2,003.55	72.41	2,009
Makár	2,005.02	65.85	1,998
Csicsó-hegy	1,900.54	100.87	1,896

In the Villány Hills the elevations of vineyards range from 100 to 279 m *(Table 4).* Higher elevations have a lower chance of frost damage in cold winters. In two consecutive winters of 1985–1987 frost severely affected large areas at the foothills. Similarly, lower elevations, due to higher relative humidity values, have a larger potential for fungal diseases. Elevation ranges are up to 132 m. Summit vineyards and Kopár have the lowest range. Kopár is located lowest (122 m) and Csicsó-hegy is the highest (234 m).

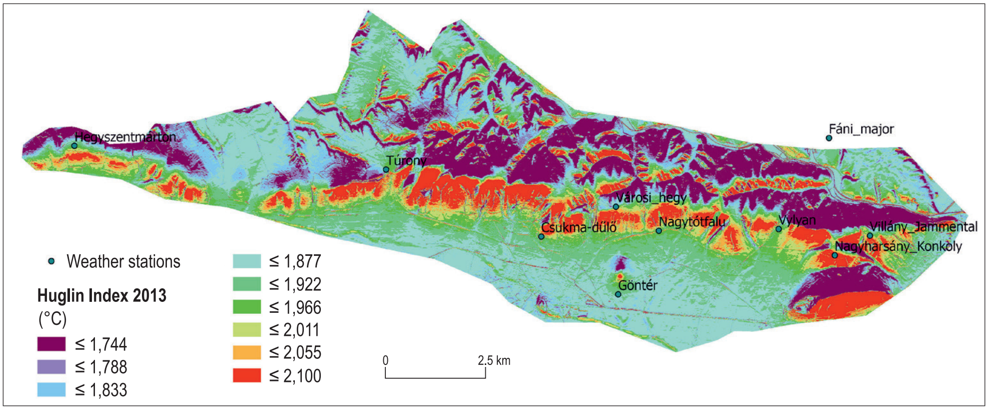

Fig. 5. Spatial distribution of the Huglin Index in the studied area

Table 3. Spatial statistics of aspect for the ten studied vineyards

Vineyard	Min, °	Max, °	Range, °	Mode, °	Mean, °	Abs 180-mean, °
Hársos	2.29	297.76	295.47	177.96	177.95	2.05
Várerdő	212.47	341.57	129.09	284.18	297.24	117.24
Fekete-hegy	175.24	316.91	141.67	191.00	192.02	12.02
Kopár	147.99	209.05	61.06	176.67	180.61	0.61
Csillag-völgy	0.00	357.09	357.09	176.18	177.40	2.60
Ördög-árok	7.13	325.01	317.88	154.71	164.85	15.15
Imre-völgy	50.71	206.03	155.32	175.84	175.81	4.19
Mandolás	132.34	247.89	115.55	176.68	173.33	6.67
Makár	120.43	225.00	104.57	175.55	171.12	8.88
Csicsó-hegy	0.00	345.96	345.96	197.07	195.18	15.18

Table 4. Spatial statistics of elevation for the ten studied vineyards

Vineyard	Min, m	Max, m	Range, m	Mean, m	STD	Median, m
Hársos	147	235	88	195.76	24.29	200
Várerdő	130	223	93	168.21	22.81	167
Fekete-hegy	141	268	127	185.54	27.73	181
Kopár	100	162	62	121.59	14.61	121
Csillag-völgy	141	273	132	197.25	40.15	187
Ördögárok	149	279	130	215.71	34.36	217
Imre-völgy	110	213	103	155.70	30.81	148
Mandolás	136	200	64	159.08	15.27	156
Makár	123	200	77	148.64	15.46	144
Csicsó-hegy	200	250	50	233.57	12.01	235

Generally, mean slope inclination remained below 10° for 9 of the studied vineyards, with the exception of Ördög-árok, where mean slope inclination reached 11.54° *(Table 5).* Vineyards in plateau positions generally had a mean slope inclination of less than 6°, hence they are preferred for viticulture.

Spatial correlations among terroir factors and must properties

The current study revealed the effect of HI, elevation, slope, aspect and soil on grape juice properties for 10 selected vineyards in the Villány Hills (*Table 6*). Elevation and slope did not show correlation with any of the VVC parameters. HI and aspect had a moderate linear relationship with 5 VVC parameters with r^2 ranging between 0.5045 and 0.6954. HI showed a correlation with four nitrogen related parameters (FAN, NH_3, YAN), density and glucose + fructose content, while aspect showed moderate correlation with PAN. Aspect, when determined on the basis of angular distance from South (180°) showed a strong correlation ($r^2 > 0.7$) with FAN, NH_3, YAN, sugar content (fructose + glucose) and density.

Based on cluster analysis of all studied parameters (terroir and VVC parameters), three vineyard clusters were identified *(Figure 6).* The Várerdő vineyard with dominantly NW, NNW (297°) facing slopes forms an outlier. The second cluster included the Csillag-völgy, Imre-völgy, Ördög-árok and Csicsó-hegy. In this latter cluster vineyards are characterized by relatively high relief and large topographical differences, with medium HIs. The third cluster, encompassing the Fekete-hegy, Hársos, Makár, Mandolás and Kopár vineyards included areas with the relatively low relief and high indices. In this cluster Fekete-hegy is located on gentle slopes, Kopár in a foothill position while the remaining three are positioned on flat summits in the central section of the range.

Table 5. Spatial statistics of slope for the ten studied vineyards

Vineyard	Min, °	Max, °	Range, °	Mean, °	STD
Hársos	0.45	10.42	9.97	4.86	2.00
Várerdő	1.23	21.95	20.72	7.88	4.16
Fekete-hegy	1.23	15.72	14.49	5.80	3.02
Kopár	1.47	21.96	20.49	7.77	3.77
Csillag-völgy	1.03	14.01	12.98	5.29	2.23
Ördög-árok	1.01	22.16	21.15	11.54	4.82
Imre-völgy	1.62	15.12	13.50	5.75	2.67
Mandolás	1.72	10.51	8.80	5.52	2.17
Makár	1.87	15.62	13.75	6.02	3.16
Csicsó-hegy	0.81	13.10	12.29	4.97	2.13

Table 6. Coefficients of correlation (r^2) of various VVC parameters with HI, elevation, slope inclination and aspect for the ten studied vineyards

Parameters	HI	Elevation	Slope	Aspect
Tartaric acid	0.1664	0.2183	0.0984	0.0339
pH	0.1341	0.2182	0.1105	0.0152
Malic acid	0.2657	0.0187	0.1122	0.4867
Primary amino nitrogen (PAN)	0.3671	0.0107	0.0670	*0.5766*
Free amino nitrogen (FAN)	*0.5045*	0.0099	0.0232	***0.8030***
NH_3	*0.5865*	0.0573	0.0604	***0.7957***
Yeast assimilable nitrogen (YAN)	*0.5715*	0.0288	0.0036	***0.8718***
Density	*0.5841*	0.0263	0.0225	***0.8809***
Bx	0.2389	0.0449	0.1262	0.4092
Glucose + fructose	*0.5609*	0.0061	0.0016	***0.8547***

Note: *Moderate* and ***strong*** linear relationships.

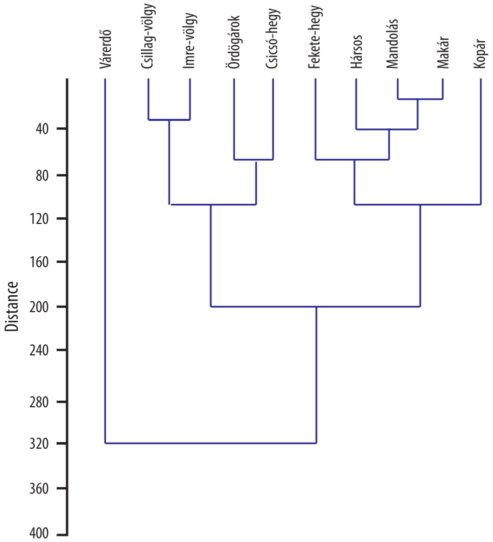

Fig. 6. Cluster analysis of the studied vineyards based on all studied parameters

Conclusions

The complexity of a terroir calls for a holistic approach to grabbing its essence. Former literature has pointed out significant spatial differences in pedological and topographical properties within single vineyards, with a subsequent spatial variability on the growth and development of the vine shoots, berries as well as grape quality (e.g. Cheng, G. *et al.* 2014; Balla, D.Z. *et al.* 2019). Although the topography and morphology of the Villány Hills are relatively simple, in accordance with the findings of former works (e.g. Ough, C.S. and Kriel, A. 1985; Ubalde, J.M. *et al.* 2010; Petrovic, G. *et al.* 2019), our results revealed a relationship among topographical properties (elevation, aspect and slope), soil variability and selected chemical properties of the grape juice. Hence, alongside the spatial patterns of management techniques (Coller, E. *et al.*

2019), the infinite combinations of biophysical factors generate a great diversity of terroirs in the area. Explaining the distribution of rocks, slopes, soils, water availability, microclimate and natural vegetation, in our opinion, the topographic pedosequence is an equally complex concept, which is capable of reflecting many of the essential properties of a terroir.

Nonetheless, functional relationship has only partially been found between the various abiotic and chemical properties. The probable reason for this is the complex influence of abiotic factors on must quality, and, in general, on the physiology of the grape. Therefore, the terroir cannot be broken down into a series of individual indicators. Favouring relatively gentle slopes and considerable soil depths, the majority of the studied vineyards are found in either foothill or plateau positions. This heterogeneous topographical distribution, is found to be at least partially reflected in VVC chemical properties, including FAN, NH_3, YAN, sugar content and density. Soils of the Villány Hills, found on plateaus and foothill positions tend to have deeper root systems and grow on a soils of higher organic matter content, as organic matter either remain non-transported (plateaus) or is transported to the gentle slopes of foothill positions (Kenderessy, P. and Lieskoský, J. 2014; Kirchhoff, M. *et al.* 2014). Equivocally with the results of Tardaguila, J. *et al.* (2011), soils in the southern slopes of the Villány Hills, mixed with colluvial sediments in foothill positions tend to have higher clay contents therefore likely have a higher cation exchange capacity and more plant available moisture contents.

Further upslope, however, above the zone of colluvial materials, organic matter and clay contents tend to decrease, reaching the lowest values in the zone of inflection. Nonetheless, vertical variation of this sort is likely occur in soils developing along a toposequence, where the prevailing soil forming factor is topography, discussed in details by e.g. Meinert, L. and Busacca, A. (2002), Repe, B. *et al.* (2017) and Vrščaj, B. *et al.* (2017). This type of spatial pattern of soil qualities generates more fertile soils with clay-loamy textures and higher water holding and supplying capacities at footslope positions whereas fertility and mean moisture contents decrease with increasing elevations (Busacca, A. and Meinert, L. 2003). However, in correspondence with the findings of Wilkins, D. and Busacca, A. (2017) obtained under similar climatic and topographic conditions to those of the Villány Hills, we also concluded that local meso- and microclimate, and in general geodiversity (Stepišnik, U. *et al.* 2017) may significantly influence the locality-specific terroir properties and wine quality through the spatial pattern of soil properties.

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Soil moisture retention on slopes under different agricultural land uses in hilly regions of Southern Transdanubia

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Abstract

Increasingly severe weather extremes are predicted as one of the consequences of climate change. According to climatic models, weather extremities induce higher risks for both flood and drought in the Carpathian Basin. Throughout the 19th and 20th centuries, flood control relied on cost-intensive engineering structures, but recently ecological solutions have come to the fore. Flood hazard on major rivers could be mitigated if multiple and cumulative water retention opportunities are exploited on the upper sections of tributary catchments. Appropriate land use and landscape pattern changes can shift the infiltration to run-off ratio to the benefit of the former. In the Transdanubian Hills of Southwest Hungary three study areas with different agricultural land use types had been selected and investigated for the impact of landscape micro-features on soil moisture retention capacity with the purpose of conserving water from wet periods for the times of drought. Marked differences in moisture dynamics have been detected between arable land, grasslands and orchards. This fact underlines the need for integrated soil and water conservation. Drought risk was found to be the highest on ploughland. Favourable soil water budgets have been observed in the fields as a function of land use: less intensive types, like grazing land and orchards (particularly tree rows), were identified as places of high water retention capacity. Although serious water stress conditions were also reached in the orchard, it markedly mitigated drought conditions compared to the ploughland.

Keywords: water retention, water stress, soil moisture dynamics, ecosystem services, land use, landscape micro-features, Pannonian Basin

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Introduction

The reports of the Intergovernmental Panel on Climate Change (IPCC) unequivocally predict growing spatial and temporal concentrations of precipitation for the 21st century (IPCC 2013). This trend is manifested in different manners regionally, but for the Carpathian Basin it involves an increase in flood hazard (Didovets, I. *et al.* 2019), particularly in flash flood hazard (Fábián, Sz.Á. *et al.* 2006; Czigány, Sz. *et al.* 2010; Lóczy, D. *et al.* 2012). Flash floods are disastrous rapid run-off events, which can be generated in any season by the joint effect of numerous local environmental factors and primarily affect small mountainous or hilly catchments of agricultural utilization, where they cause damage comparable to that of large river floods.

Seldom so concentrated in space and more difficult to localize, droughts are apparently less dangerous than floods (World Bank 2019).

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Although they develop more gradually, they last for much longer periods than floods (often for years). An important component of adjustment to new climatic conditions could be an integrated water management, equally directed to the prevention of floods and droughts (Grobicki, A. *et al.* 2015; Ferk, M. *et al.* 2020). Water retention is a crucial task here (European Commission 2014; Ferk, M. *et al.* 2020). The damage brought about by extreme weather events always depends on the local context. As a good example, it could be cited that in Hungary 2010 was by far the most humid year since the beginning of meteorological observations, while 2011 was somewhat drier than anything observed before (KSH 2012). In most of the mesoregions of the country, however, thanks to the storage of surplus moisture from the previous year in soils, the 2011 drought did not cause remarkable losses of crop yield.

For long, throughout the 19th and 20th centuries, flood control measures meant cost-intensive construction of engineering structures (primarily dykes and embankments). Only recently the significance of natural processes in flood control has been recognized. Indicators of flood regulation demand (Stürck, J. *et al.* 2014) allow the mapping of the distribution of areas with high flood regulation capacity, which is mostly due to close-to-natural vegetation or extensive agricultural use. The main limiting factor to flood regulation is the low water retention capacity of some soil types due to their texture, bulk density and organic matter content (Castellini, M. and Iovino, M. 2019). The relative weights of such parameters can be defined through sensitivity analyses (Bakacsi, Zs. *et al.* 2019).

It had not happened before the 21st century either that the importance of water retention on floodplains was recognized within the framework of ecosystem services (Fisher, B. and Turner, K. 2008; Haines-Young, R. and Potschin, M. 2011; Dezső, J. *et al.* 2019). This recognition induced a change of paradigm in water management: instead of getting rid of surplus water and conducting floods as rapidly as possible downstream, the main objective became the conservation of water – primarily in floodplains (Lóczy, D. 2013), but also, in small but cumulative amounts, in the upper sections of catchments (Hümann, M. *et al.* 2011). The idea is that in these sections the rapid collection of run-off waters can be prevented applying relatively simple and low-cost investments before huge water masses could cause disastrous floods on lowland river sections (Seeger, M. and Ries, J.B. 2008). How can we create conditions more favourable for slow infiltration than for rapid run-off? Certain land use classes as well as landscape micro-features can be effective in this respect (Syrbe, R.-U. and Grunewald, K. 2013). Since the intensity of infiltration tends to decrease exponentially (or in a power fashion) with time, the first hours after rainfall (or sudden snowmelt) are of particular significance.

For an integrated and sustainable water basin management a reconsideration of the role of landscape pattern and water retention capacity is needed. Instead of cost-effective engineering solutions, which are often damaging to the aesthetic quality of the landscape (Jørgensen, D. and Jørgensen, F.A. 2018; Peng, S.H. and Han, K.T. 2018), more natural, 'ecological', interventions are required (European Commission 2014), which also serve the goals of the EU Water Framework Directive and other guidelines (European Commission 2000, 2006, 2007). In the Natural Water Retention Measures (NWRM) directive the following goals are identified (European Commission 2014):

- parallel mitigation of flood and drought risk;
- regulation of stream flow and surface run-off to intensify infiltration;
- enhancement of water storage in soils, standing water bodies and aquatic ecosystems;
- supporting positive natural hydrological processes.

All these measures underpin the resilience of ecosystem under conditions of climate change.

As conceived in the European Union, NWRM (European Commission 2014) comprises both traditional (waterways, retention ponds etc. – Declerck, S. *et al.* 2006) and novel solutions ('soft engineering' such as green infrastructure, bio-infiltration, rain gardens etc.)

which are relatively easy to apply in urban (Pyke, C. *et al.* 2011) as well as rural environments (Emerson, C.H. *et al.* 2005; Davis, A.P. *et al.* 2009). The efficiency of retention measures should be carefully monitored in the context of the local environment (Výleta, R. *et al.* 2017).

A carefully chosen type of land use on hillslopes can be the best tool for run-off regulation (Leitinger, G. *et al.* 2010; Zucco, G. *et al.* 2014; Ribeiro, D. and Šmid Hribar, M. 2019). The modelling of run-off generation and water conservation under different agricultural land uses, modified by the spatial and temporal variability of soil physical properties, is a common topic of research in Europe (e.g. Stolte, J. 2003), the United States (Guerrero, B. *et al.* 2017) and China (Wang, H. *et al.* 2013). The findings are applied in land-use planning.

In addition to the effect of land use on run-off, various authors have identified a range of manmade features in traditional landscapes (hedgerows, scarps on field margins, ploughland terraces, riparian belts) which are instrumental in run-off deceleration (Baudry, J. *et al.* 2000; Thiem, K. and Bastian, O. 2014; Šmid Hribar, M. *et al.* 2017) and have a number of other beneficial functions (wind shelter, conservation of air and soil moisture, soil erosion and pollution control etc.). In the 20th century, the loss of traditional management practices has led to a large-scale impoverishment of the landscape (Wei, W. *et al.* 2016) and declining biodiversity (Haber, W. 2014). At the same time, some landscape elements prove to be persistent and survive. For instance, ploughland terraces (in German: *Ackerterrassen*) are still conspicuous elements of many agricultural landscapes (Lóczy, D. 1998). Even relict micro-topographic elements (occasionally with remnant vegetation patches) can modify slope processes (run-off, erosion, nutrient fluxes – Zorn, M. and Komac, B. 2011; Centeri, Cs. *et al.* 2015) and are particularly highly appreciated in regions where water is in short supply (Chen, L. *et al.* 2013; Niu, C.Y. *et al.* 2015). It should be noted that occasionally escarpments and terraces completely deprived from vegetation are also efficient since the slope deposits which are often accumulated in considerable thickness store substantial amounts of moisture. Economic calculations confirm that their conservation is profitable: it is claimed that the expenses of conservation yield returns with 1.8-fold average profit in the future (Thiem, K. and Bastian, O. 2014).

Retention ponds on small watercourses help to reduce extreme water regime (Gotoh, H. *et al.* 2011; Ferk, M. *et al.* 2020) and release floodwater gradually into major rivers (Scholz, M. 2003). The return of the expenses of such investments is also regarded favourable (IUCN 1997; Berry, P. *et al.* 2017). In Hungary, in the Transdanubian Hills numerous flood retention reservoirs (on many streams in a cascading system) were built in the 1970s. The largest, Lake Deseda, is capable to store 10.75 million m^3 of water (Cser, V. 2019). Although it was built for the purposes of flood control and industrial water supply, the reservoir is of complex utilization, i.e. also used for fishing and angling, bathing, nature conservation, water sports and other recreation activities. These secondary functions, however, can occasionally conflict with the primary one. Although retention reservoirs are remarkable landscape features, their landscape ecological role has not been surveyed yet (Ferk, M. *et al.* 2020).

The efficiency of resilient measures of flood control is excessively analysed in water management and landscape ecological literature (Kundzewicz, Z.W. *et al.* 2018). Run-off retention is one of the most important regulating ecosystem services from the viewpoint of water management (TEEB, 2010; Haines-Young, R. and Potschin, M. 2011; Laterra, P. *et al.* 2012; Horoszné Gulyás, M. 2012; Stürck, J. *et al.* 2014). A range of relatively easily established or maintained landscape features, including diversion or contour banks (DERM 2010), grassed waterways (Fiener, P. and Auerswald, K. 2003), vegetated ditches (Cooper, C.M. *et al.* 2004; Moore, M.T. *et al.* 2004; Otto, S. *et al.* 2016), hedgerows and other buffer strips (European Union 2014) are routinely used in landscape planning worldwide. Historical surveys are performed in the ongoing Hungarian national project on the mapping and evaluation of ecosystem services (MAES-HU – Tanács, E. *et al.* 2019). The three services selected for monetary evaluation also include water retention capacity.

The Topographic Wetness Index (TWI) developed by Beven, K.J. and Kirkby, M.J. (1979) and further refined by Beven, K.J. (1986), identifies sites of run-off concentration on slopes and, thus, depicts the detailed spatial distribution of moisture storage. Plenty of experience is available on the applicability of the TWI, not only for run-off control (Hjerdt, K.N. *et al.* 2004), but, for instance, for spatial vegetation pattern (Kopecký, M. and Čížková, S. 2010), for delimiting inundated areas after urban flash floods (Pourali, S. *et al.* 2016) and for the spatial extension of NVDI index values (Sharma, A. 2010). The index was found to be suitable for hilly areas but proven to be misleading in the case of broad floodplains and flat valley bottoms with deep sediments fills where large amounts of water are stored (Ali, G. *et al.* 2013). No experiments of this type have been performed so far in the Pannonian Basin.

The current paper presents the first findings of a joint Hungarian-Slovenian research project entitled "Possible ecological control of flood hazard in the hill regions of Hungary and Slovenia". According to the authors' knowledge no studies have been targeted the analysis of the impact of linear landscape elements on moisture retention in the Pannonian Basin. The project aims at filling in this scientific gap and exploring the opportunities of water retention in soils on hillslopes in a sustainable manner and without costly investments into hard engineering structures. In addition to the analysis of the impact of land use change, the impact of landscape features on water dynamics during the vegetative period of 2019 was also studied.

Materials and methods

Study sites

The three study areas are located in the Transdanubian Hills of Southwest Hungary in the vicinity of the city of Pécs *(Figure 1).* All three has relatively gentle slopes, similar soil parent materials (loess) and physical soil types. The agricultural land use types and landscape patterns (the preservation of traditional landscape elements), however, are different (ploughland, pasture and orchard).

Boda area (foothills of the Mecsek Mountains)

This study area is located about 10 km West of Pécs, in the southern foreland of the Mecsek Mountains, gently sloping towards the Pécs half-basin. Its elevation ranges from 172 to 182 m. Typical land use is large-scale arable farming with conventional tillage, with sugar-beet, cereals, sunflower, soy and rape seed as the main crops. The prevailing diagnostic soil type of the site is Haplic Luvisol. The soil moisture monitoring sites were placed on a slope of 4.24 per cent inclination. It means that this surface can be regarded as almost horizontal, but the steepest slopes with southern or south-western exposure have angles up to 10 per cent. The distance between the upper and the lower monitoring sites is 190 m. Erosion features in the study area include a derasional valley and an erosional stream with a small grove which influences soil moisture budget in the immediate vicinity of the valley. Heavy rainfalls between 3 and 16 July 2018 induced large-scale rill erosion on the surface. The annual rainfall of the area in 2019 totalled 630 mm.

Palkonya area (northern foreland of the Villány Hills)

The second study area lies enclosed between the settlements of Palkonya, Ivánbattyán, Kisjakabfalva, Villány and Villánykövesd. The parent material is loess overlying a Mesozoic limestone basement. The soils are described as Chromic Cambisols. Elevation above sea level is somewhat lower than in

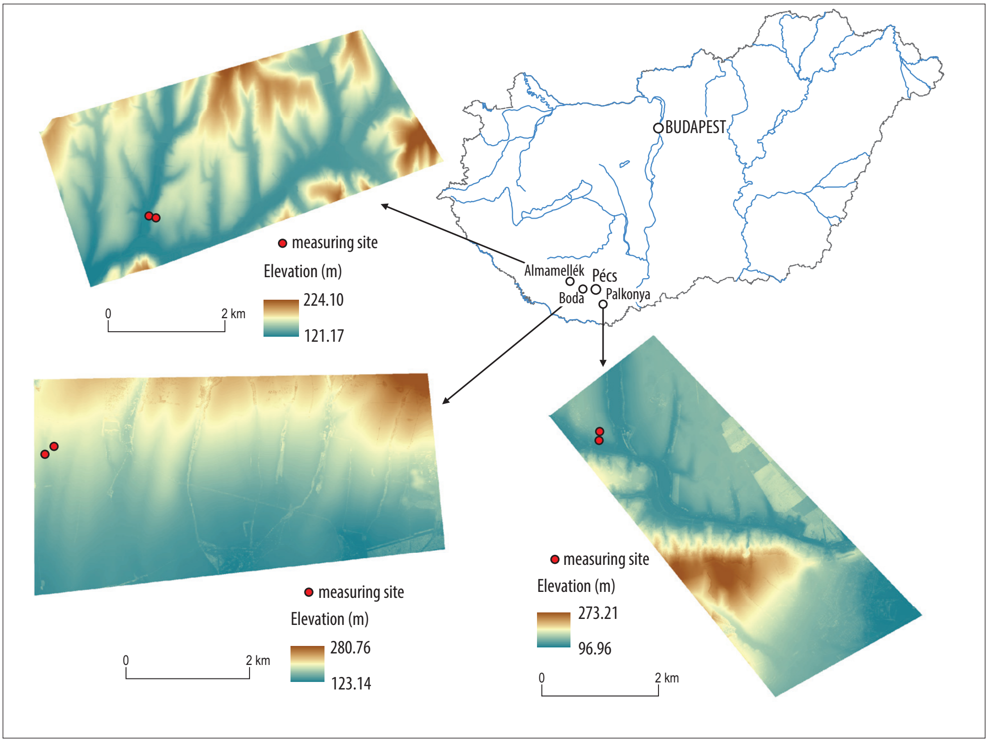

Fig. 1. Location of the study areas on the DEM generated from a LiDAR survey. a = Almamellék (meadow); b = Boda (arable land); c = Palkonya–Villánykövesd (orchard)

Boda, 113–128 m, while the plot where the monitoring equipment is placed is steeper, with an average slope of 8.98 per cent. Land utilization is partly orchard and partly grazing land. The measurement sites were deployed at a distance of 156 m from each other. The annual rainfall of the area in 2019 totalled 830 mm.

Almamellék area (Zselic Hills)

The study area is situated in a basin of the Zselic Hills at an elevation of 127–142 m. Its relief is subdued (mean slope angle is 4.24%) but still slightly dissected. The Calcaric Phaeozem soils of the site are locally severely eroded. (The Hungarian Agricultural Plot Registration Database [MePAR] indicates medium to severe water erosion hazard for ca 40% of the study area.) The valleys are used as meadows and hillslopes mostly as grazing land. The measurement sites are located at a distance of 167 m from each other. The soil and water conservation measures implemented by landowners to date have not proved to be efficient. The most significant rainfall event of the past decades was observed in March 2018 with a total rainfall of 128 mm recorded by the rain gauge of the neighbouring Szentlászló which threefold exceeded the long-term March average. A rapid and sediment-loaded run-off washed down huge amounts of loess along dirt roads used by agricultural vehicles into concrete-lined water-conducting ditches even plugging culverts. The annual rainfall of the area in 2019 totalled 770 mm.

Generation of the TWI_{LU} *maps*

For a comprehensive assessment of the water dynamics the Water Retention Index (*WRI*) was employed, which is a useful tool to estimate potential water retention broken down to water storage by the various landscape components (Vandecastaele, I. *et al.* 2016; Qiu, Z. *et al.* 2017; Raduła, M.V. *et al.* 2018). The WRI is calculated using the following equation:

$$WRI = (w_v R_v + w_{gw} R_{gw} + w_s R_s + w_{sl} R_{sl} + w_{wb} R_{wb}) \cdot (1 - \frac{R_{ss}}{100}), \quad (1)$$

where w is the weight to be assigned to each parameter (subscript v is vegetation, gw is groundwater, s is soil, sl is slope and wb stands for surface water bodies), and R is the parameter scores given for retention in vegetation (R_v), groundwater bodies (R_{gw}), soil (R_s) and surface water bodies (R_{wb}), and for slope (R_{sl}) and soil sealing (R_{ss}). The values of the component factors of the equation were estimated from findings of other research projects in Hungary (Kertész, Á. *et al.* 2010; Juhos, K. *et al.* 2019).

An indispensable precondition for the experiments carried out in the study areas was a Digital Elevation Model (DEM) of proper resolution. While a 1-m resolution DEM based on LiDAR survey for the territory of Slovenia (Žvokelj, B.P. *et al.* 2015) was at the disposal of the Slovenian partners, unfortunately, for the territory of Hungary no such suitable DEM was available. Therefore, as a first step a LiDAR survey and the subsequent data processing into a DEM was ordered and carried out by the Envirosense Hungary Ltd. The limitations of project financing only allowed for the survey to cover three study areas, 11–12 km^2 each.

In principle a DEM can be applied to depict soil moisture conditions because water flow tends to follow topographic gradients and accumulate in response to gravitational potential energy (Murphy, P.N.C. *et al.* 2009). Therefore, for reconstructing the spatial distribution of moisture storage and the sites where surface run-off is concentrated, the Topographic Wetness Index (*TWI*) is widely used (Beven, K.J. and Kirkby, M.J. 1979).

TWI is a GIS-based index which can be derived from any grid with elevation data and is able to indicate the soil moisture conditions and water retention potential, solely based on topography. Relying solely on the DEM, the TWI_{DEM} only identifies the sites of natural run-off concentration and the resulting distribution of soil moisture. This way the importance of topography is exaggerated and, at the same time, the role of land use is disregarded. Eventually, TWI relies on a high-resolution DEM and calculates water and soil moisture distribution only from the size of the catchment area and slope inclination as input parameters, using the following equation:

$$TWI = \ln(a / \tan \beta), \quad (2)$$

where a is the number of DEM pixels above the point of observation (representing the catchment area) and β is slope inclination (in degrees). TWI is a dimensionless figure, which ranges from 0 to 30. Values close to 0 indicate dry areas, while those above 20 wet areas. In the light of previous investigations (see e.g. Murphy, P.N.C. *et al.* 2009; Drover, D.R. *et al.* 2015; Thomas, I.A. *et al.* 2017), special attention should be devoted to the quality of input data for TWI, primarily to their resolution. Experiences with the application of TWI confirmed that calculation merely corresponds with topography and cannot realistically reflect soil moisture conditions. Therefore, as a further developed version, Beven, K. and Wood, E.F. (1983) and Beven, K.J. (1986) suggested a Soil Topographic Wetness Index (*STWI*), which also takes into account soil and sediment transmissivity (in the saturated zone below the groundwater table):

$$STWI = \ln\,(a/T \cdot \tan \beta), \quad (3)$$

where T is soil and sediment transmissivity (below groundwater table) measured in $m^2 h^{-1}$. From the DEM $\tan \beta$ is the slope, while the value of $\tan \beta = \partial/\partial L$ is more applicable for the evaluation of biodiversity and soil pH (Sørensen, R. *et al.* 2006).

TWI index values were calculated with ArcGIS 10.4 software. The input model was the DEM generated from LiDAR survey data and the Digital Surface Model (DSM) of 1-metre resolution. The latter dataset included the first reflectance of the radar signals, and, therefore, comprises all natural and artificial objects (in other words, DSM represents the elevations of the reflective surfaces [trees, buildings and other features] which rise above the ground surface – Zhou, Q.M. 2017).

Natural water retention potential was assumed to be proportional with the difference between the TWIs calculated from the DEM and from the DSM. It was supposed that the features of micro-topography with water retention potential have some (even if minimal) spatial extension and, therefore, are represented in the DSM as higher-lying surfaces. Subtracting the elevations of pixels in the DSM-derived TWI from the DEM-derived TWI, the difference can be any value (negative, positive or zero). To avoid results of negative values, the minimum grid value (*m*) in the investigated area (always negative) is subtracted from the difference of the DEM and DSM derived TWI. The new TWI applied for land use (TWI_{LU}) is calculated grid by grid using the following equation:

$$TWI_{LU} = TWI_{DEM} - TWI_{DSM}) - m, \qquad (4)$$

where TWI_{LU} is water retention potential; TWI_{DEM} is TWI grid value derived from the DEM; TWI_{DSM} is the TWI grid value derived from the DSM; $m = \min(TWI_{DEM} - TWI_{DSM})$ is the minimum value of the difference between TWI_{DEM} and TWI_{DSM} within the study area. The grid values therefore can only be positive numbers or zero. As a consequence, values ranging from 0 to the median value can be regarded to indicate areas with low water retention potential, while areas with values ranging from the median to the maximum value are designated as areas with high water retention potential.

Field monitoring setup

To validate the soil moisture model in the context of the local landscape pattern, soil moisture monitoring systems were installed for each study area in December 2018. Rainfall totals and intensities were collected using tipping-bucket rain gauges (ECRN-100, Meter Group Inc., Pullman, WA, Unites States) of 0.2 mm resolution. Rain gauges were installed only at the top of slopes of plots. At both the top and bottom of each monitored slopes TDR soil moisture sensors (Meter Group Inc., Teros 12) and tensiometers (Teros 21) were horizontally inserted into the soil at depths of 10 and 30 cm. All data were collected with EM-60 data logger in 15-minute time intervals.

For the spatial calibration of the model, Volumetric Water Content *(VWC)* was measured with a Fieldscout TDR-300 soil moisture meter (Spectrum Inc., Planfield, Illinois, United States) in June 2020, following a dry winter and spring (184, 175, 195 and 187 mm rainfall totals between January 1 and May 31, 2020 in Pécs, Almamellék, Boda and Palkonya, respectively). Fifty measurements of three repetitions at each measurement point were taken at the three sites using 20-cm long electrodes. Spearman analysis was employed to compare TWI_{LU} maps with the field measured data.

Particle size analysis of the soil samples

Soil samples were taken from the depths of 10 and 30 cm. Samples were then pre-treated for the removal of organic matter and $CaCO_3$ in the soil science laboratory of University of Pécs. Textural pattern and particle size distribution of the soil samples were determined using a Malvern MasterSizer 3000 (Malvern Inc., Malvern, England, United Kingdom) particle size analyser.

Results and discussion

Distribution of TWI indices in the study area

According to former studies land use plays an important role on the spatial distribution of soil moisture. To this purpose, the DSM (controlled by land use) was integrated into the DEM to create a combined DEM-DSM (called TWI_{LU} in the current study), uniting moisture dynamics (water retention) originating from topography and from land use. Therefore, the calculated TWI_{LU} was used to depict the spatial distribution of soil moisture in the three study sites.

TWI_{LU} maps showed patterns noticeably different from those on either TWI_{DEM} or TWI_{DSM} maps *(Figure 2)*. The obtained TWI_{LU} maps indicated the potential run-off paths which were due to the joint effect of topography and vegetation (land use) in the three study areas. In addition to micro-topography, the TWI_{LU} also indicated the influence of landscape features, in the case of the orchard, tree rows, on run-off reduction and moisture storage (see *Figure 2*). TWI_{LU} distinctly pointed out the combined role of surface elevation and vegetation (elevated surfaces) on the spatial distribution of soil moisture in the three study areas.

The overall highest TWI value was detected at the Almamellék site (28.080). The TWI_{LU} map indicated low TWI values at the abrupt step (location of the top slope station) of about two metres vertically at the top of the Almamellék site and at the dirt road in an upslope direction. Although enhanced lateral evaporation was expected here in the profile, tension did not fall below the permanent wilting point (PWP, -1,500 kPa) during the entire monitoring campaign. It is likely explained by the low infiltration and lower roughness values of the road which enhance run-off in the direction of the step and the tensiometers. The site of the bottom slope station here was not properly selected and should have been positioned in the main stream of moisture accumulation about 65 m to the south. However, if located closer to the fish ponds the effect of groundwater would be more pronounced on moisture contents.

The TWI_{LU} grid values of the Boda site were the lowest among the three sites with a maximum pixel value of only 17.754. Here the TWI_{LU} map indicated pixels of high moisture contents for both monitoring stations, due to the proximity of the hedgerow upslope of the top slope station and the influence of the grove upslope of the bottom slope station. Still, this site was exposed to the greatest water stress over the monitoring campaign with tension below PWP for the longest period. Here, the lack of crop cover, following the harvest, likely contributed to the low matric potential values. However, additional moisture and tension data were not available to compare the two stations with in-site moisture data where micro-features did not influence moisture dynamics.

At the Palkonya site soil moisture showed moderate variations (TWI values ranged between 0 and 21.53). The most prominent pattern was observed at the orchard site where the tree rows influenced soil-atmosphere interactions via the differences in direct irradiation and evapotranspiration. The TWI index allowed a clear distinction between surfaces with the predominance of run-off and those with high water retention capacities. The latter mostly coincide with the rows of trees (see *Figure 2*). Run-off in the orchard was diverted into the alleys between tree rows, while canopy differentiated water retention through interception, shading effect and evapotranspiration, hence modifying the infiltration/run-off ratio. Nonetheless, in a considerable portion of the Palkonya site, spots of high water retention were not parallel with the tree rows. This fact underlines the modifying effect of natural micro-features in relief. This heterogeneous moisture pattern is pointed out in the TWI_{LU} model, however it does not always reflect higher water retention capacities along the tree rows compared to the interrows (*Figure 2*, i).

Soil moisture and tension distribution based on field monitoring

Monitored matric potential (ψ_m) data for the spring period revealed that capillary rise (upward water motion) was the dominant process at the upper sites while at the footslopes infiltration (downward water motion) dominated moisture dynamics *(Figure 3)*. Matric potential

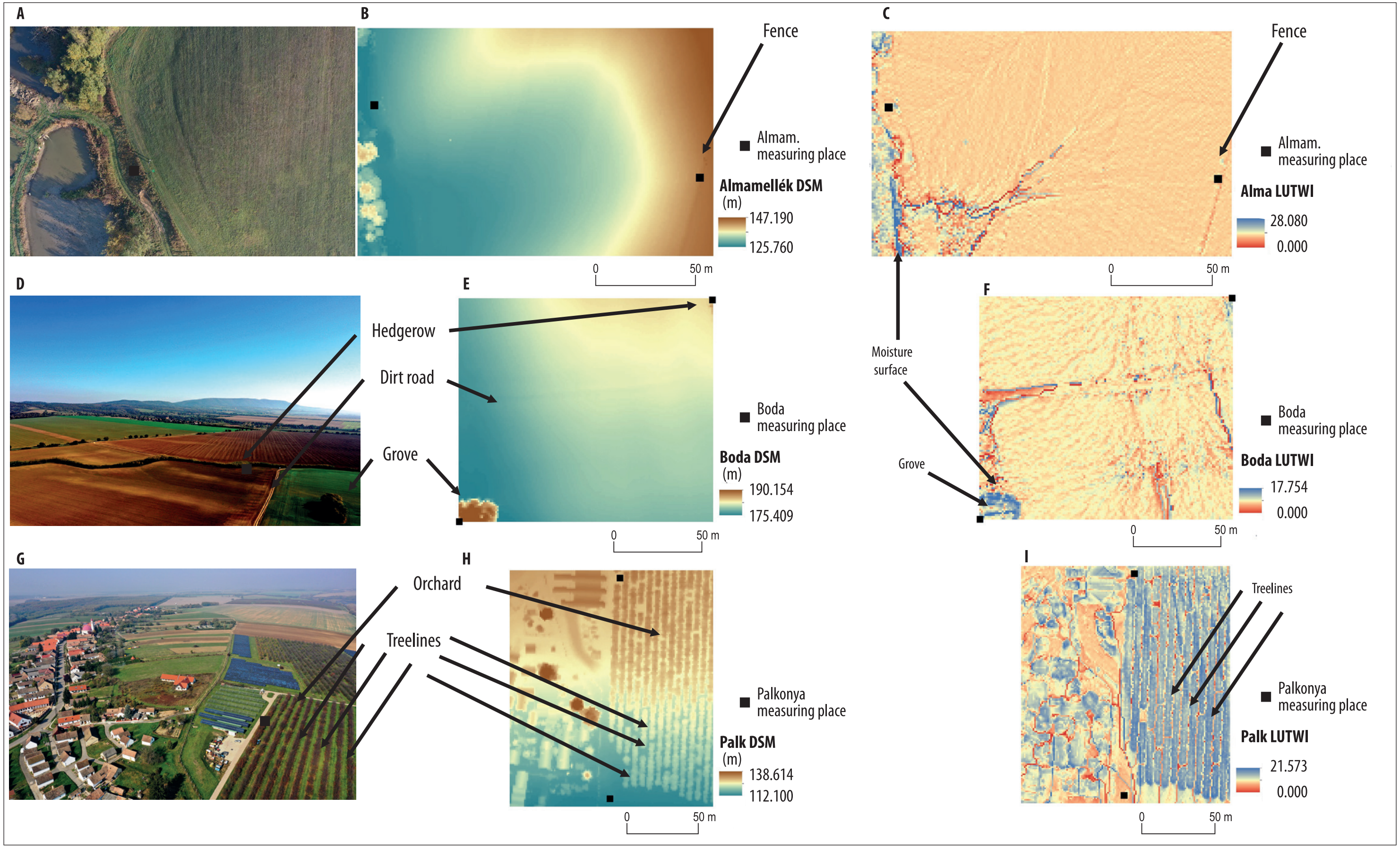

Fig. 2. Land use of the study sites: a = Almamellék meadow; d = Boda ploughland; g = Palkonya orchard. DSM model of the sample sites: b = Almamellék; e = Boda; f = Almamellék; c, f and i = TWI_{LU} model

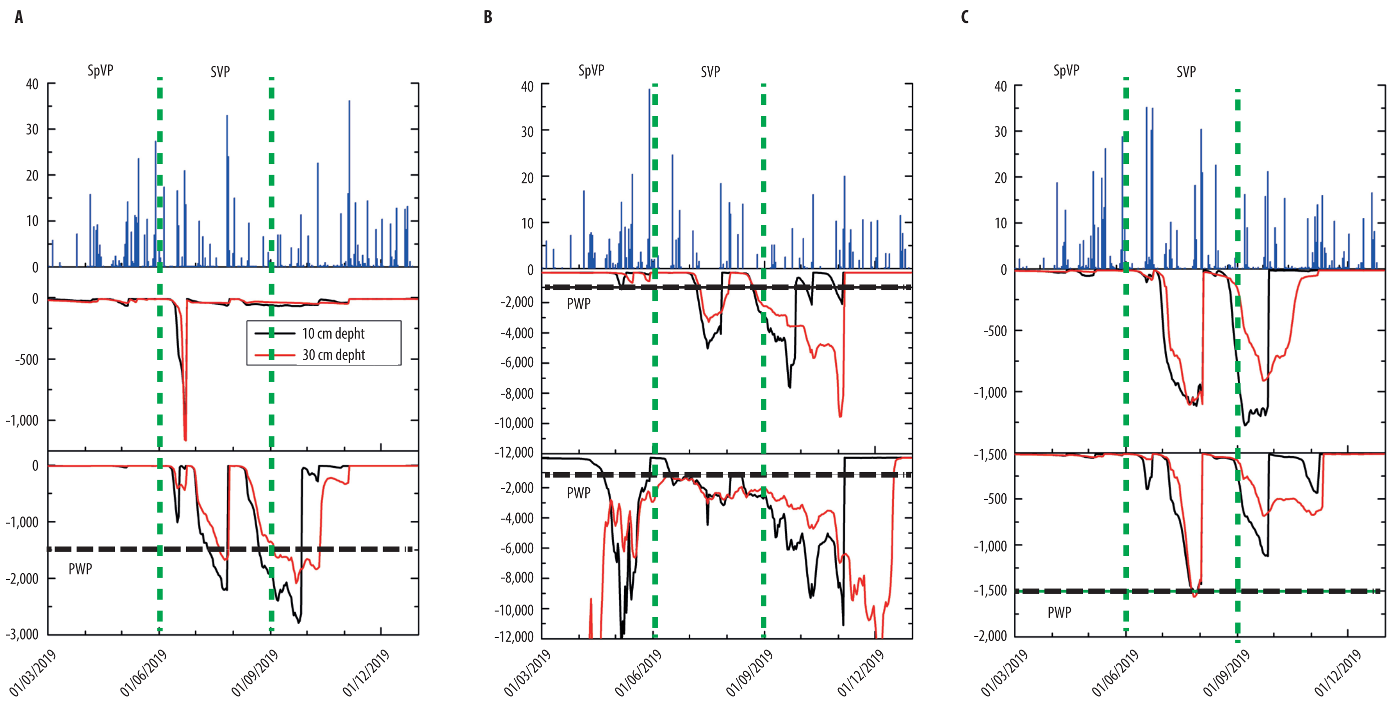

Fig. 3. Measured hydrometeorological data from the study sites: a = Almamellék; b = Boda; c = Palkonya. Tension 1 = top-slope station; Tension 2 = bottom-slope station

values observed at the three study sites were remarkably different over the investigation period. Similarly, differences in water potentials were striking between the spring and summer periods of the growing season.

There was no significant difference between the fluctuation of the top-slope and bottom-slope potential values during the spring season at the Almamellék site. Here, tension values did not fall below the PWP. Prolonged periods devoid of rainfall triggered the plunging of water potential from -20 kPa to -1,300 kPa between July 1 and 13, 2019, at both the top-slope and the bottom-slope station. However, for the rest of the summer water potential at the top-slope site did not fall below -250 kPa. Water potential at the bottom-slope station fell below the PWP twice. Former studies also concluded that usually there are two periods of drought hazard in Hungary (Kocsis, T. and Anda, A. 2006). However, no rainless period exceeded 15 days over the study period.

The Boda site is utilized for dryland farming, hence it remains uncovered by crops for a prolonged period of time between September and April (see *Figure 2*). This plot is bordered by a hedgerow to the northeast, while a grove borders the plot to the southwest: these features significantly mitigate run-off at the aforementioned boundaries of the studied plot. Mean tension values in the spring, measured next to the hedge, were higher (-25 kPa) than next to the grove (-65 kPa) (*Figure 3*, b). While tension did not fall below the PWP during the spring, there were no plant available water next to the grove in the top 30 cm between March 28 and May 28. Water potential fluctuations were an order of magnitude higher next to the grove than at the hedge. During this period, two rain-free spells lasted for 10 days (March 26 to April 4) and April 15 to 24). During the summer water potential fell below the PWP at both the hedge and the grove. Tension remained below the PWP for the entire summer at the grove. Although tension also fell below PWP at the edge of hedgerow, a major difference was observed between the length of drought-affected period between the top-slope and the bottom-slope sites. The grove matric potential remained below -1,500 kPa during the entire period at a depth of 30 cm, and even further decreased till mid-November (*Figure 3*, c). Sub-PWP tensions abruptly ceased on October 30, 2019, at both top-slope depth and at a depth of 10 cm at the bottom slope (grove) when tensions increased due to a rainfall event of 10.3 mm. However, tension at a depth of 30 cm at the grove remained below the PWP. At the hedgerow two distinct drought period was identified: the first between July 8 to 27 and a second between August 27 to September 27.

At the Palkonya site, the top-slope station is located among the trees while the bottom-slope station is found 8 m downhill from the base of the orchard (see *Figure 2,* c). During spring tension was never less than -25 kPa (note that the moist-end measurement limit of Teros 21 is around 8 kPa). Fluctuation of tension was almost negligible in the spring months. Over the summer top-slope tension never fell below the PWP, yet tension decreased from -33 kPa to -1,104 kPa. Tension at the bottom-slope station, however, reached the PWP for 3 consecutive days between July 27 and 29, 2019.

Water stress sensitivity

Our research validated former results (Emerson, C.H. *et al.* 2005; Davis, A.P. *et al.* 2009; Leitinger, G. *et al.* 2010; Syrbe, R.-U. and Grunewald, K. 2013; Wang, S. *et al.* 2013; Zucco, G. *et al.* 2014; Výleta, R. *et al.* 2017), i.e. soil moisture is closely controlled by land use, the proximity of land features, precipitation totals and intensities and soil textural properties. During our monitoring campaign precipitation totals of less than 1 mm per day did not affect matric potential. In terms of temporal variability of matric potential of the topsoil, two significant periods, characterized by large fluctuations and relatively low tension, were observed at all three study sites. Tension only fell below the PWP at the ploughland and the meadow sites, while reached the PWP at the bottom-slope station of the orchard. Largest variability of matric potential was observed at the grove-ploughland and the hedge-ploughland boundaries. At the meadow site the bottom slope was affected by medium tension fluctuation while the orchard bottom-slope tension was only slightly sensitive and exposed the vegetation to only a slight water stress. Presumably, the grove and the hedgerow functions as a water retention barrier during run-off events, whereas during periods of water stress they may further decrease soil moisture contents and the matric potential of the top 30 cm of the soil. Although rainless periods were always shorter than 15 days, which contradicts the findings of Kocsis, T. and Anda, A. (2006), agricultural an economic drought was still extensive, especially at the tilled site. Land use change does not actually eliminate the appearance of drought but shortens its duration and mitigates its impact on vegetation.

In the spring period the most favourable soil water budget was observed in the grazing land of Almamellék, where average soil moisture content was the highest in summer. Drought risk in summer was the highest in the Boda area. Soil moisture contents were low on many occasions and for prolonged periods. The longest of such periods lasted for 46 days (between June 17 and August 2, 2019). During summer the Palkonya orchard, a close-to-natural type of agricultural land use, had the highest average soil moisture content, particularly if we compare it with the built-up area in its western neighbourhood. This finding confirms that even very sparse, village-type, housing development may have a considerable negative impact on moisture conditions (see *Figure 3*). Analysing the interrelationships between precipitation and tension, for the Palkonya area it was found that rainfall events above 1 mm could cause observable changes in tension of the upper soil horizon.

Soil moisture distribution influences soil formation processes on the long run. Depending on the season and the morphological position remarkable differences are observed in the direction of water motion (infiltration versus capillary rise). At the measurement sites water tensions at 10 and 30 cm depths as well as their temporal changes differed conspicuously between the upper and the lower sites of measurement. The footslope sites invariably had less negative matric potentials. It was found that in spring capillary rise can alternate with infiltration along the same slope. The limited surface run-off observed at all the three areas can be explained by the low rainfall intensities and gradual snowmelt. During the summer part of the growing season capillary rise was common for both measurement sites. Horizontal flow (surface run-off and probably throughflow too) has intensified in the summer compared to spring. This particularly applies to major showers (e.g. on June 18, 2019: 35.2 mm day^{-1}, on August 3, 2019: 30.4 mm day^{-1}).

Our results revealed a weak correlation between elevation and field measured VWC for the orchard (Palkonya site), moderate correlation for the ploughland (Boda site) and strong correlation for the pasture of the Almamellék site *(Table 1)*. TWI_{LU} performed well pointing out spatial variation in soil moisture conditions and dynamics at the orchard site, as TWI_{LU} integrated both the effects of topography and vegetation. By accounting for the shading effect and retention of moisture under canopy, TWI_{LU} well reflected actual moisture contents of the top 20 cm of the studied soils. When elevation was correlated with the TWI_{LU}, the orchard showed the highest correlation and the pasture the weakest, demonstrating the adequacy of TWI_{LU} for a land use type of this sort. When the measured VWC was correlated with TWI_{LU}, negative correlation was found

Table 1. Correlations among elevation, VWC and TWI_{LU} for the three studied land use types

Parameters	Ploughland	Orchard	Pasture
Elevation – VWC	0.573	0.354	0.726
Elevation – TWI_{LU}	0.357	0.790	0.087
VWC – TWI_{LU}	-0.438	0.412	0.139

Note: VWC was measured during an extreme dry period in June 2020.

for the ploughland while the best correlation was observed again for the orchard site. The negative correlation demonstrates water retention in upslope and midslope position, likely indicating the influence of linear elements (a grove and a hedgerow) in the intensively cultivated landscape which counteracts and reduces the downslope movement of soil moisture due to gravity.

According to our findings, the most favourable soil water conditions have been observed in the grazing land and orchards (particularly tree rows), as they were identified as places of high water retention capacity. These findings have been partly corroborated by the conclusions of Wang, H. *et al.* (2013) who claim that grasslands in Eastern China had the highest infiltration rates preceding shrubs, subshrubs, trees and crops. However, mean soil moisture contents were only the second highest in their study and were lower than under maize canopy. According to Výleta, R. *et al.* (2017) linear elements (e.g. tree rows and hedgerows), perpendicular to slopes, stabilize the surface, prevent soil denudation and mitigate direct run-off and water erosion, while, at the same time, contribute to increased infiltration. According to our findings, however, tree rows parallel to the slopes also mitigate run-off, and, combined with the shading effects of tree canopies, induce higher soil moisture contents compared to interrows.

Furthermore, Davis, A.P. *et al.* (2009) based on the result of their case study, suggest the strategic use of surface vegetation to divert and reduce surface flow and to filter sediments. Emerson, C.H. *et al.* (2005) sound the view that the volume control of peak run-offs in watersheds of high relief solely by detention basin is ineffective, unless combined with other alternative land use and run-off management practices. In accordance with the latter statement, Hinman, C. (2005) points out the necessity of sustainable practices and low-impact technologies on complex stormwater management. Similarly to Emerson and his co-workers, we found that run-off volume can be controlled by grasslands and pastures, which contributes to increased infiltration and mitigate direct run-off.

Leitinger, G. *et al.* (2010) found that the greater the initial soil moisture content, the smaller the influence of slope gradient on run-off and infiltration remained. This finding was also confirmed by our results: increased infiltration was observed at lower initial matrix potential values. However, Leitinger and his colleagues attributed particular importance to the seasonal dynamics of surface run-off and the land use type in their experiments performed in the Stubai Valley, Eastern Alps, Austria. Their experiments, in contrast to our results, revealed that macropore flow was inhibited on pastures due to the compaction exerted by cattle. The change in bulk density at depths of 0 and 0.2 m may have affected water holding capacities and recharge rates at the intensively cultivated Boda study site in or experiments. Hence, structural changes and increased soil bulk densities reduce macropore volume, macropore flow and soil moisture recharge. This also suggests that trampling, treading and mechanical load by heavy machinery may affect soil structure, which may be avoided by various BMPs including conservation tillage or no-till techniques (e.g. Fuentes, J.P. 2004).

In contrast to the findings of Tölgyesi, C. *et al.* (2020), we did not observe the desiccating effect of trees on lower soil layers. This is partly explained by the difference in soil textural types as the aforementioned study found the drying effect in soils of sandy textures. On the contrary, our results revealed that in the case of the orchard trees, canopy and the shaded area enhances water retention and water storage during dry periods and therefore contributes to the general functions of natural ecosystem services. This finding is in a good agreement with those of Syrbe, R.-U. and Grunewald, K. (2013), and Ribeiro, D. and Šmid Hribar, M. (2019), who accredit high ecological importance to semi-natural line elements in the management of excess storm water. According to Guerrero, B. *et al.* (2017), in harmony with our findings, also suggest that natural agricultural water conservation strategies are capable to limit the decline of water and soil moisture supplies at regional scales. In addition, and rather similarly, our results pointed out the importance of natural landscape elements, providing ecosystem services, on the spatial distribution of soil moisture and water retention at sub-regional plot scales.

Conclusions

Our field monitoring results revealed that soil moisture at depths of 10 and 30 cm did not fully correspond with the spatial pattern of neither the TWI_{DEM} nor the currently presented TWI_{LU}. Rather unexpectedly, field-monitored data always indicated lower (more negative) tension values for the bottom slope sites than for the top-slope sites (see *Figure 3*). Naturally, this pattern contradicts the pattern of TWI_{DEM} and TWI_{LU} as both calculation algorithms assume the influence of gravity on moisture dynamics. This discrepancy can be partially explained by the influence of linear pedological and vegetational features and landscape elements (like in the case of the Almamellék site, with an anthropogenic step at the top of the slope) on the distribution of soil moisture, not fully reflected in the TWI_{LU} map.

A second possible reason for the observed discrepancy is the insufficient resolution of field monitored data. To improve the spatial resolution of soil moisture distribution, point soil moisture measurements were taken using a mobile TDR device. The latter high-resolution soil moisture measurements corroborated the large spatial heterogeneity of soil physical properties (texture, macropores, and preferential flow paths) in the field as well as the influence of landscape elements on soil moisture dynamics.

A third explanation for the difference in soil moisture pattern between the field pattern and the TWI_{LU} map is the large spatial heterogeneity of soil physical patterns, especially the difference in soil texture. Therefore, the careful selection of the long-term soil moisture and water potential monitoring sites is essential. Alternatively, as mentioned in the previous paragraph, mobile monitoring of topsoil moisture conditions could provide a substitute solution for field data acquisition.

A fourth reason for the possible deviation between the TWI maps and the field data lies in the relatively short equilibrium time that was available for the sensors after deployment. The insufficient contact between the sensors and the presence of voids around the sensor discs might have supplied erroneous tension data. Therefore, longer periods of field monitoring, and higher cumulative infiltration totals and the subsequent compaction of soil particles are essential to verify and obtain an objective overview of field soil moisture patterns.

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Crop growth, carbon sequestration and soil erosion in an organic vineyard of the Villány Wine District, Southwest Hungary

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Abstract

A more resilient adaptation to changing climate calls for crop diversification in vineyards, too. As a contribution to the H2020 collaborative project of the European Union, called Diverfarming, and part of the agroecological experiments during 2018 and 2019, grapevine biomass growth was monitored in connection with carbon storage types in soil and in the deposits removed by soil erosion. Phenometry was carried out interpreting segmented images to follow changes in biomass. It was found that crop growth could be best described by the Richards growth function. The distinction between grapevine and intercrop growth, however, requires further refinement in image analysis. In the laboratory TOC and N_{total} were measured for both the soil and the plant organs as well as for the eroded sediments. Greenhouse gas emissions and photosynthesis were monitored. Looking at the change of Leaf Area Index (LAI) over the growing period, image analysis pointed out the role of cut shoots from pruning in the C and N cycles. Maximum leaf area (at ripening) for guyot cultivation technique was extimated at 7,840 m^2 ha^{-1}. Soil loss by erosion was established by sediment traps at the end of vinestock rows. The grain size distribution analysis led to the remarkable result that as erosion proceeded, the ratio of the sand fraction increased but remained within the range for the textural class of loam. Organic matter contents grew to 38 g kg^{-1}. The rate of soil erosion is higher in ploughed than in grassed interrows by orders of magnitude.

Keywords: crop diversification, organic vineyard, phenometry, Leaf Area Index, C/N ratio, carbon sequestration, biomass, image analysis, soil erosion

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Introduction

A major actual challenge for agriculture is the establishment of sustainable cultivation technologies without yield or income loss. The Horizon 2020 collaborative project Diverfarming (Crop diversification and low-input farming across Europe: from practitioners' engagement and ecosystems services to increased revenues and value chain organisation) strives to increase the long-term resilience, ecological sustainability and economic revenues in many branches of agriculture across the EU (EIP-AGRI 2020). This objective is to be achieved through raising the provision level of ecosystem services, assessing

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the real benefits and minimizing the limitations, barriers and drawbacks of diversified cropping systems under low-input practices. Tailor-made sustainable solutions are sought for six European pedoclimatic regions. In the Pannonian pedoclimatic region, the Hungarian partners run case studies in horticulture (an asparagus field) and in the vineyard of Gere Attila Winery. Some early results from the latter are presented here.

Crop growth should be monitored in response to environmental factors varying with time. The growing period of grapevine can be divided into three sections:

- Fruit set, when it is decided what portion of the grape inflorescence will develop into berries;
- Veraison (”change of colour”), i.e. the onset of sugar accumulation and rapid berry pigmentation by anthocyanins in red grapes;
- Berry ripening, synthesis of a high diversity of aroma compounds mostly to the effect of hormones and ethylene (Kuhn, N. *et al.* 2014).

Castellarin, S.D. *et al.* (2007) claim that in the early growth period water deficit accelerates the process of sugar accumulation and induces anthocyanin synthesis and even after veraison increases anthocyanin accumulation. Water deficit negatively affects berry size (Ojeda, H. *et al.* 2001), but Greer, D.H. and Weston, C. (2010) confirm that moderate water deficit, UV-B radiation, and low temperatures positively affect ripening by increasing the content of total soluble solids and anthocyanins, while high temperatures, shade, and pathogens hinder ripening. Temperature rise is manifested in the sensory traits of berries and this is relevant for wine-making (Vilanova, M. and Soto, B. 2005; Sadras, V.O. *et al.* 2013). The responses to heat stress, however, vary with cultivar and season.

In each period the efficiency of assimilation of the canopy is a vital factor (Delrot, S. *et al.* 2010). In modern viticulture crop and canopy growth are strictly regulated in the production of appelation wines (Matthiasson, S. 2013). If yield is restricted, the vegetative growth of vinestocks is promoted. Bunch spacing or cluster thinning is a common practice in many vineyards worldwide (Naor, A. *et al.* 2002; Lőrincz, A. *et al.* 2003; Creation Wines 2014). The common goals meant to be achieved by yield restriction are higher alcohol levels, darker colour, riper fruit, reduced greenness and acidity, modified tannic composition – properties which are, however, not desirable for all wine varieties.

The quantitative and qualitative parameters of canopy do not only influence yields but also the carbon cycle and carbon sequestration in soils (Marras, S. *et al.* 2015; Nistor, E. *et al.* 2018). Insolation, air humidity, wind and other meteorological parameters modify vine canopy development and assimilation. Medium or long-term biomass accumulation in the soil is a function of canopy management practised to obtain a vegetative balance, i.e. to avoid exaggerated shoot growth.

Climate change mitigation is a major ecosystem service of vineyards. The principal greenhouse gas (GHG) in vineyards is N_2O – with equally harmful effects as excessive CO_2. The optimal timing of nitrogen fertilizer application can reduce the impact (Nendel, C. and Kersebaum, K.C. 2004; Longbottom, M.R. and Petrie, P.R. 2015). Carbon is contained in all organs of grapes as well as in soil organic matter. Carbon sequestration in soil through minimized tillage, compost/mulch application and reduced factor passing can only be detected after many years (Wolff, M. *et al.* 2013). Recently, cover crops have been used to reduce GHG emissions, but in certain environments, like the Mediterranean region, there may be severe competition for resources (Celette, F. *et al.* 2008). Recent studies, however, show that intercrops do not increase water stress compared to bare-soil vineyards (Delpuech, X. and Metay, A. 2018). Nevertheless, on shallow soils decreased yields can be expected as the cover crop coverage is increased above a threshold (of 30% in the Mediterranean region of France). The Mediterranean trend of climate change makes these observations relevant for Hungary.

The rate of canopy development from April to June varies from year to year and exerts a decisive influence on the oncoming phenophase. The net assimilation and transpiration rates of grape canopy are a decisive factor in determining yield and grape juice quality (Kozma, P. 2001, 2002). The Leaf Area Index (LAI), i.e. the ratio of leaf area to cropping area, is a widely used indicator of the rate of photosynthesis and transpiration (Fuentes, S. *et al*. 2014). To determine LAI using the point quadrant (PQ) method is widespread in wine regions (Silvestroni, O. *et al.* 2018) as a standard analysis (Wilson, J.W. 1963; Smart, R. and Robinson, M. 1991). Hyperspectral images of Unmanned Aerial Vehicles (UAVs) are useful in the estimation of LAI through the generation of a 3D grapevine mass surface model (Kalisperakis, I. *et al.* 2015). Calibration resulted in a correlation of $R^2 = 0.73$. Tractor-mounted LiDAR was used for LAI determination in the vineyards of Catalonia (Arnó, J. *et al.* 2012).

In Hungary we could not find any publication on the estimation of LAI, but GreenSeeker 505 vegetation sensors were applied in the wine region of Tokaj-Hegyalja combined with Normalized Differential Vegetation Index (NDVI) and relationships between grapevine growth and soil water budget were pointed out (Riczu, P. *et al.* 2018).

For the continuous monitoring of crop growth remote sensing techniques are of increasing significance. The application of UAVs and hyperspectral cameras placed at low heights opened a new chapter in the investigation canopy biomass in vineyards (Arnó, J. *et al.* 2012; Badr, G. *et al.* 2015; Kalisperakis, I. *et al.* 2015). The closer the sensors are set to vinestocks, the more precise detection can be expected (Towers, P.C. *et al.* 2019). The techniques of image processing have kept pace with the image capturing technology. There is an equal focus on both vegetative growth and berry ripening (Whalley, J. and Shanmuganathan, S. 2013). Studying daily evapotranspiration of vine, Semmens, K.A. *et al.* (2016) found that hyperspectral techniques can support water management strategies. Automatic detection of pests, for instance, of *Flavescence dorée*, proved to be successful (Al-Saddik, H. *et al.* 2019). The application of the SPA Successive Projection algorithm ensures more than 96 per cent accuracy in pest detection. RGB (red, green and blue images superimposed), multispectral and thermal imagery is widely employed to assess vineyard variability and to monitor the evolution of grapevine parameters to support precision viticulture and decision making (Pádua, L. *et al.* 2020). RGB images taken by UAV were used to estimate canopy mass and LAI in Texas (Mathews, A.J. and Jensen, J.L.R. 2013) and in Savoy (Comba, L. *et al.* 2019), where a correlation of $R^2 = 0.82$ was attained.

Our experiments take place in an organic vineyard of the Villány Wine District. Organic viticulture is rapidly spreading worldwide because it offers multiple advantages over conventional cultivation (Probst, B. *et al.* 2008; Provost, C. and Pedneault, K. 2016), producing high quality grapes and wines with lower inputs, conserving biodiversity and keeping pests and diseases at low levels. In organic viticulture only organic fertilizers and non-synthetic pesticides are allowed and soil disturbance is reduced by minimum tillage and grassing (Meissner, G. *et al.* 2019). Biodynamic viticulture, where specific preparates are applied to enhance bacterial action, is also popular in many countries (Meissner, G. *et al.* 2019). In southern France conversion to organic viticulture was found to significantly increase bulk density, total organic carbon content (TOC) and cation exchange capacity (CEC) of soils (Coll, P. *et al.* 2011). These findings point to higher soil quality. In the experiments microbiological benefits were also remarkable: much higher microbial biomass carbon, nematode and omnivore, plant-feeder and fungal densities were found in organic plots. After an initial decrease in nutrient (N, P, K) contents, values began to rise when microbial life established itself and released organic acids. The earthworm populations, however, did not show increases (probably explained by more soil compaction) (Coll, P. *et al.* 2011).

Soil erosion in vineyards with steep slopes depletes soil fertility and indirectly reduces the quality of grapes and wine (Rodrigo-Comino, J. *et al.* 2018). A large variety of soil conservation measures are proposed (from minimum tillage to mulching and even geotextiles – Kertész, Á. *et al.* 2007). Their successful application, however, is heavily dependent on local conditions. Numerous papers deal with the advantages of organic farming with respect to soil erosion (see e.g. Kirchoff, M. *et al.* 2017).

Along with its benefits, organic viticulture has to face numerous challenges not only in cultivation and nutrient supply but also in plant protection. Excluding synthetic pesticides from among the alternatives of plant protection can lead to higher incidence of downy and powdery mildew and yield loss. In organic farming, Cu is approved and commonly applied for downy mildew caused by the fungus *Plasmopara viticola* (Döring, J. *et al.* 2015) but it leads to a hazardous extent of Cu accumulation in soils. Weed control is another topic where organic viticulture needs innovations (Baumgartner, K. *et al.* 2009; Bekkers, T. 2011). In California mechanical weed management was found most effective and economical, without affecting grape yield or quality (Shrestha, A. *et al.* 2013). In contrast, in the vineyard studied in the present project cover cropping is the primary means of plant protection supplemented with the application of Cu compounds, biostimulants enhancing induced resistance and feromon dispensers (Steenwerth, K.L. and Belina, K.M. 2008; Werner, J. and Forgács, B. 2016).

Related to the issues mentioned in the Introduction, the main questions to be answered by the present research were the following:

- How does biomass production change in the various phenological phases of grapevine development? This can be revealed by phenometric investigations.
- How the values of Leaf Area Index (LAI) reflect these changes over the growing season? To answer this question field monitoring and calculations were necessary.
- What is the medium-term impact of the above trends on carbon sequestration? To this end, laboratory analyses of canopy, biomass, different properties of soil and eroded sediment were performed.
- How much organic matter is lost by soil erosion from the bare alleys between vinestock rows? The amounts were estimated by field monitoring and laboratory analyses of soil sediment samples.

Study area

The study area lies in the Pannonian pedoclimatic region, in the Villány Wine District, Baranya County, Southwest Hungary (coordinates: 45°51‘47.8“N, 18°26‘39.6“W – *Figure 1*). Mean annual temperature is 10.7 °C (1981–2010) average annual precipitation is 680 mm, annual potential evapotranspiration is 650 mm (1981–2010). Maximum monthly rainfall was 186.8 mm (May 2010), while maximum daily rainfall was low in comparison with other regions: 53.2 mm (on 23 April 1942 – Hungarian Meteorological Service, OMSz). Most recently in June 2009, heavy hail affected 400 ha of vineyard area and created run-off carved gullies of 50–70 cm depth.

The plantation has been cultivated for several centuries on southern slopes of 15–20° inclination with loamy, slightly calcareous and compacted Ramann's brown forest soil, in the World Reference Base system (IUSS Working Group WRB 2015: Chromic Cambisol). At the experimental plot soil depth is 1.7–2.0 m. Average humus content in the topsoil (uppermost 30 cm) is 3.36 per cent (with standard deviation of $r = 0.36$), total carbon content (C_{total}) is 25.96 g kg^{-1}, C/N ratio is 17.13. In soils N mineralization is well balanced. Susceptibility to water erosion is high on the hillslopes.

The Gere Attila Winery has vine plantations of 70 ha, out of which the Diverfarming experiment covers 1.36 ha. Apellation wine is produced in the premium vineyards of Kopár, Feketehegy, Ördögárok (*Teufelsgraben*) and Csillagvölgy (*Sterntal*). The main red grape varieties grown over 75 per cent of land are Cabernet Franc, Cabernet Sauvignon, Merlot and Portugieser. Guyot training (cane prun-

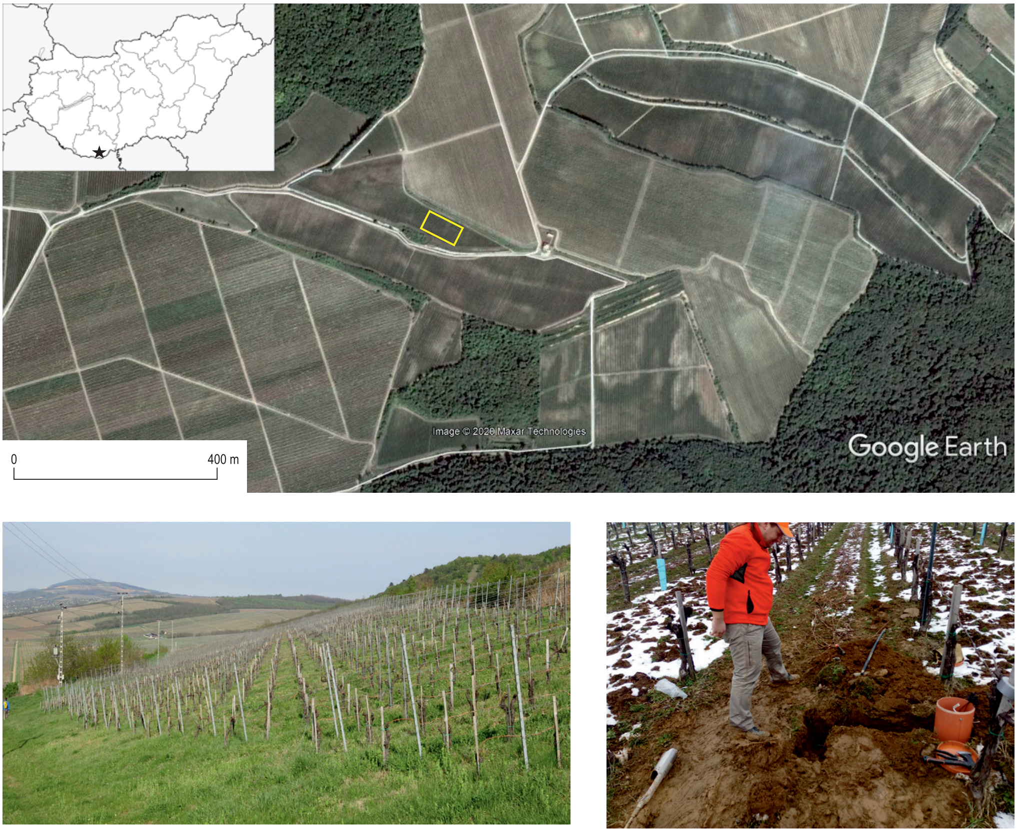


Fig. 1. Location of the study area: Konkoly vineyard, Villány Wine District, Baranya County, Southwest Hungary (Base map: GoogleEarth, photos by Dezső, J.)

ing – Puckette, M. 2016) is predominant with a planting density of 2.3 times 0.6 stocks (7,200 stocks ha^{-1}) (Werner, J. and Forgács, B. 2016). Organic viticulture was extended from 11 ha in 2009 to the entire vineyard area in 2019. Bud density is reduced to 2–4 buds m^{-2} to regulate yield. Most of the vineyards are of mature age, the oldest was established in 1992.

Vinestock interrows/alleys are sown with a mixture of grass and leguminous herbs at five- or six-year intervals. The species composition of cover crops is altering spontaneously. Interrows are mown on four or five occasions during the growing season. Hay is left on the ground to slowly decompose and add to soil organic matter. As a control treatment vineyard plots without interrow vegetation are instrumented.

Methods

Image capture, processing and analysis

To obtain reliable data on crop growth, remote sensing should take place as close to the vinestocks as possible (Towers, P.C. *et al.* 2019). Covering extensive areas simultaneously, the application of Unmanned Aerial Vehicles (UAVs) for imaging is an option, but day-to-day monitoring using UAV is difficult to implement. If a camera fixed on a pole is used, upscaling to areas of several hectares is corrected by supplementary calibration. With the above considerations in mind, to follow the growth of both grape plant and intercrops (the extent of their surface coverage) cameras were placed on high poles *(Photo 1).*

The principal criteria the images had to meet were the following:

– Individual leaves had to be well detectable in the image;

– The cameras had to be able of both night (infrared) and day imaging;

– The distances between posts and cordon wires could be used as reference points in image interpretation.

The selected equipment was a DÖRR SnapShot Multi Mobil 3G 16MP HD camouflage camera, usually applied as a low-angle (58°) wild camera. Supplied with 60 LED lights of 940 nm wavelength, it is also suitable for night imaging. Images were taken at 30-min intervals and forwarded to the server of the Faculty of Sciences, University of Pécs. Two cameras were placed on a 6-m high pole serving multiple purposes: observations of biomass growth, cultivation interventions in interrows and traces of erosion at the end of rows *(Photo 1).* Each image covers six full vinestocks.

The growth of individual leaves and the canopy was reconstructed from the images using ImageJ 1.52S software. Image processing aimed at expressing percentage growth relative to the portrayed area. Unfortunately, because of the changeable illumination, this task could not be fully automated (as described by Fuentes, S. *et al.* 2014). Careful manual processing was employed to avoid false interpretation. A crucial step is the setting of colour threshold level with the Li algorithm (Li, C.H. and Tam, P.K.S. 1998) to allow marked distinctions in the colour image (Tajima, R. and Kato, Y. 2011). A colour composite of the grape leaf was selected. If the colour of the leaf of the cover crop is too similar to that of the grape, the error increases. Therefore, images taken in the morning were preferred for the segmentation *(Figure 2).*

Photo 1. The monitoring system for crop growth (Photo by Dezső, J.)

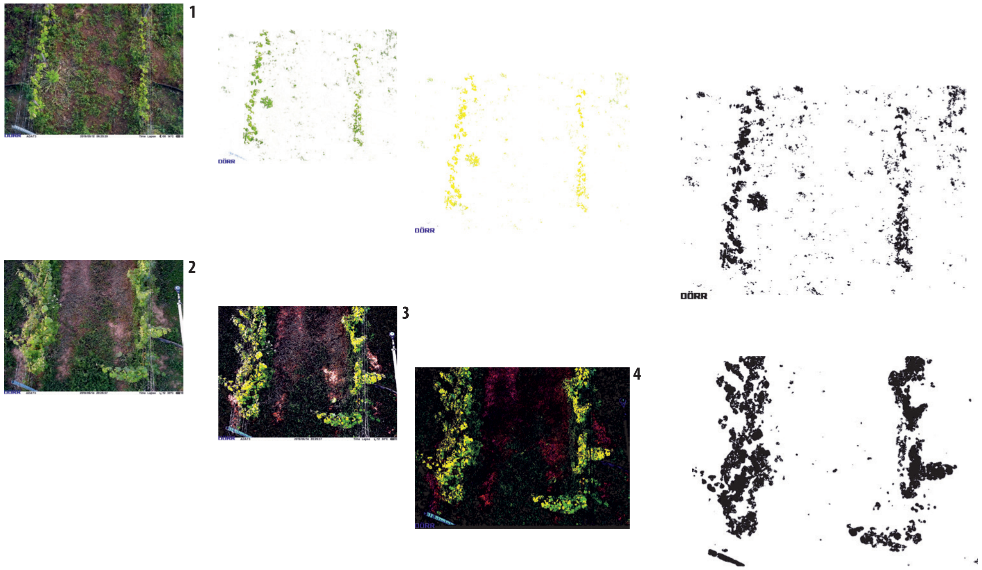


Fig. 2. Steps in fragmentation (by Dezső, J). 1 = conversion of the image to scale; 2 = colour enhancement; 3 = setting colour threshold: white background, HSB or RGB colour code, using Li or MaxEnthropy method; 4 = processing the binary image: filling holes, skeletonizing, despeckling, dilating or eroding image

The binary image was converted to scale, i.e. the number of pixels was counted on 1 cm distance, and, accordingly, the software computed leaf area.

Estimation of leaf area growth

The value of momentary leaf area per hectare land was calculated from the equation:

$$A = T \cdot H \cdot HL \cdot AL, \qquad (1)$$

where A is leaf area per hectare ($m^2\ ha^{-1}$); T is vinestock density (number ha^{-1}); H is shoot density, shoots per stock (number); HL is leaf density, leaves per shoot (number); AL is area of individual leaves (m^2).

The data on the dynamics of leaf area and biomass growth are converted into dry mass per hectare using the equation:

$$A = I_{BIN} \cdot LL_A \cdot F, \qquad (2)$$

where A is leaf area per hectare ($m^2\ ha^{-1}$); I_{BIN} is grape leaf area measured in the binary image (%); LL_A is total leaf area in the vertical leaf storeys (m^2); F is multiplying factor to extend data over 1 ha area (-).

In order to establish the LL_A value, a statistical survey of leaf amount per vinestock was performed under fully developed conditions at 27 sites of the experimental area and expressed both as area and dry mass. Assuming a uniform growth rate of leaves, the F multiplying factor was regarded constant.

In summary, the leaf areas segmented from the individual images were extended to 1 ha vineyard area using data from the survey of leaf areas of vinestocks. The standard deviations of input data ranged from 20 to 30 per cent (occasionally reaching 40%). Leaf biomass can be calculated from the mass of dry leaves (expressed in kg ha^{-1} or t ha^{-1}).

C/N ratio in biomass and soil

C/N ratio is calculated for the grapevine and intercrops (roots and stalks). C and N contents are established at high temperature in oxygen-rich environment using the Dumas technique elaborated in 1831 (OIV 2009; Agüera Buendía, E. and de la Haba Hermida, P. 2019). The measurements are carried out by a LECO CHN628 elementar analyzer. Carbon is determined by non-dispersive infrared absorption and nitrogen by a Thermal Conductivity (TC) Cell at the Department of Environmental Systems Science, ETH, Zurich. Well-homogenized samples are heated to over 1,000 °C in a high-temperature furnace where the combustion takes place rapidly in the presence of pure oxygen. Nitrogen oxides are converted into molecular nitrogen, combustion products were removed by helium gas and then nitrogen gas was obtained when conducted through hot copper. Absorbent traps are used to remove water and only N_2 and CO_2 are left behind. Total nitrogen content is measured by a thermal conductivity detector.

Organic carbon in the soil and sediments was determinated by wet combustion (OC_{wc}), using the Tyurin method (Jankauskas, B. *et al.* 2006). The dried samples were mixed with potassium chromate and extracted by concentrated sulphuric acid. The decanted and filtered liquid was measured by photometric method at 485 nm wavelength.

The same protocol was applied for soil samples. To obtain total organic carbon (TOC), the major energy source of microbial life in soils, a five-hour treatment with 10 per cent hydrochloric acid was used.

Instead of the Dumas combustion method (Cambardella, C.A. and Elliot, E.T. 1992), the standard humus determination method based on OC_{wc} measurement is widely used in Hungary. In the Diverfarming project in situ parallel soil investigations include the determination of total carbon (C_{total}), TOC and calculated total inorganic carbon (TIC).

Nitrogen forms in soils

Soil mineral N-forms (nitrate, nitrite and ammonia) represent the pool of nitrogen available to the crop and determined by the very sensitive and specific Griess-Ilosvay method (Keeney, D.R. and Nelson, D.W. 1982) using Nanocolor 500D VIS photometer (Macherey-Nagel Gmbh, Düren, Germany). After treatment with potassium-chloride and homogenization, the soil samples (taken from 10 cm and 30 cm depths) are centrifuged at 3,000 rotations per min for 10 min and KCl is decanted. Nitrite ions react with sulfanilic acid and 1-naftil-amin solution and induce red azo-dye formation. Both N-forms are measured at 520 nm in the spectrophotometer.

Soil carbonate

Topsoil carbonate contents (calculated C_{carb}) were determined by Scheibler calcimeter using 10 per cent hydrochloric acid. The carbonate forms are released and CO_2 is generated. The amount of the developed CO_2 is converted to $CaCO_3$.

Particle size measurement

Particle size distributions of topsoil samples were determined via a static light scattering technique using a Malvern Mastersizer 3000 Hydro LV (Malvern Inc., Malvern, United Kingdom) particle size analyser at the Szentágothai Research Centre, University of Pécs. During sample preparation OM was removed by H_2O_2 and shell fragments by 20 per cent HCl. The wet dispersion method allowed for a detailed measurement of grain sizes from 0.01 μm to 2,100 μm.

Greenhouse gas flux measurements

Soil fluxes of greenhouse gases have been monitored in 2018–2019, employing 51 sampling events typically 1–3 hours before local noon. This protocol was approved following preliminary investigations in 2018. The method is described in Regina, K. and Hüppi, R. (2019). Altogether 18 pieces of non-transparent static chambers of 25 cm diameter and

5 cm height (of own design) were arranged evenly among rows and interrows. Samples were taken by a syringe into evacuated vials of 20 ml at t = 0, 10, 20, 30 minutes from the closure of the chambers for gas chromatographic analysis. Fluxes of methane, carbon dioxide and nitrous oxide were calculated from the accumulation rate of concentrations in the chamber during the sampling.

Erosion measurements

In our case Gerlach troughs (Gerlach, T. 1967) could not be applied without soil disturbance during installation (Kinnell, P.I.A. 2016). Neither did the width of alleys between vine rows and slope length favour Gerlach troughs. Twelve sediment traps (three in bare interrows and three times three in the interrrows with cover crops) designed specially for the vineyard were placed at the end of vine rows in the experimental plot *(Photo 2)*. The eroded sediment was collected in 30-litre barrels. Vertically set flexible rubber bands were used to retain sediment and not to disturb mechanized vine cultivation.

Results and discussion

Parametrization of biomass growth

The estimation of biomass growth is based on the growth of grape leaves and shoots and the development of the intercrop modified by the removed biomass of berries.

Phytotechnological interventions

Both generative and vegetative productions are controlled by bud load and its distribution regulated by pruning. The guyot canopy shape

Photo 2. Sediment trap with eroded material on 26 May 2018 (Photo by Dezső, J.)

(Puckette, M. 2016), applied in the study area, is characterized by a narrow, fan-like, photosynthetically active profile *(Photo 3).* In regulated plantations the canopy serves intensive growth. Bud burst usually occurs in early April and the camera could detect the first buds in the second half of April. By that time, the nutrients necessary for shoot growth have been already stored in the vinestock. Intensive shoot growth ends in mid-June when shoots reach the height of the uppermost wire (at 160 cm). From bud burst on, over the first half of the leaf growth period, leaves require more assimilated matter than they are able to produce.

At the beginning of bloom leaf thinning induces the increase of total leaf area. On each shoot 10–15 leaves are desirable. Thinning shoots (to 6–7 shoots per stock) in early May can also regulate the number of clusters and leaf area. Cutting shoots short can induce vegetative growth from the end of June to late August. Mechanized vine 'hedging', i.e. pruning off the over-hanging current-season growth at veraison, was applied at 2 m height and removed ca 15 per cent of the vine biomass. Self-shading should be avoided through reducing the canopy wall to 2 m. In the phase of ripening bunch spacing is applied in premium vineyards to prevent vegetative (2–4 $m^2 kg^{-1}$ leaf area per yield) and generative (0.5–1.5 $m^2 kg^{-1}$ leaf area per yield) overload *(Figure 3).*

In the Konkoly vineyard eight phytotechnological interventions are performed to achieve these goals. Pruning follows in winter, when the cut-off vine shoots have a lower moisture content (10–15%). Dry matter adds up to 0.42–0.57 kg per stock (on the average: 0.48 kg), i.e. 3,657 kg ha^{-1} in a year. The C/N ratio of shoots ranges from 90 to 1 and 100 to 1 (Kostov, O. *et al.* 1996).

Phytotechnological interventions also include intercropping. Intercrops are mown 4 or 5 times

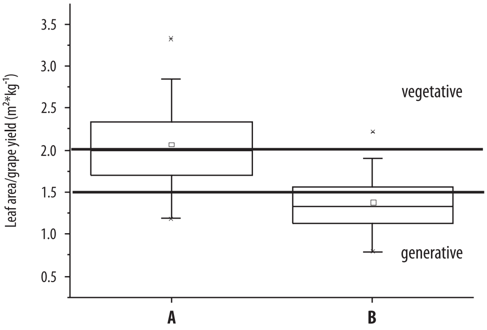
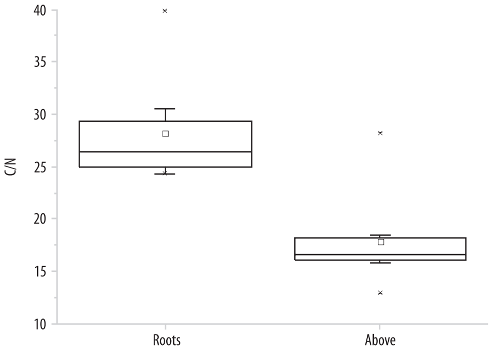


Fig. 3. Leaf area/yield ratio for 0.8 kg yield per stock (A) and for 1.2 kg yield per stock (B)

Photo 3. Vinestocks after pruning (left) and during harvest (right) (Photos by Dezső, J.)

a year and this provide 823 kg ha^{-1} dry mass. The C/N ratio of the root zone is 28.19 and of the above-ground parts is 17.88 *(Figure 4).*



	Roots, kg ha^{-1}		Above, kg ha^{-1}	
	C	N	C	N
Intercrop	39,309	1,399	311,094	18,106

Fig. 4. C/N ratios of roots and above-ground biomass, and average C and N contents of the wet mass of shoots (for m = 3,657 kg ha^{-1})

In the Konkoly vineyard sustaining manuring (30–40 t ha^{-1}) takes place in every fourth or fifth year. This involves the replenishment of 200–300 kg N (Kádár, I. 1997). Cultivation measures aim at forming 6–7 shoots per stock (of 1.38 m^2 area), 14–22 leaves per shoot and 0.8–1.2 kg yield per stock. Calculating with median values LAI is estimated at 1.156.

Average leaf area

At full canopy development, in September, 90 leaves were collected to count leaf area using the photometric method and the ImageJ software *(Figure 5).* The results were evaluated and represented by Origin 8.5 and PAST3 statistical programmes.

Estimated leaf area per hectare (calculated from Equation 2) was plotted against the critial period of growth (from 27 April). The dynamics of growth are closely correlated (R^2 = 0.99) to the Richards' trend function *(Figure 6)*:

$$\hat{y}_t = \frac{K}{\left(1 + ve^{-c(t-m)}\right)^{1/v}}$$

where $\hat{y}_t$ is the Richards' trend; K is the level of the saturation; t is the vicarial value; v ($v > 0$) influences the value of the inflexion point; c ($c > 0$) influences the function value; m ($m > 0$) is the date of maximum growth.

In the case of the experimental area the parameter values are the following: $v = 0.41$ (unitless); $c = 0.21$; $m = 25$ (day) and K is 8,493 m^2 leaf area/ha on the 60th day

Leaf storeys and cluster thinning

The number of leaf storeys along with the corresponding leaf amount were measured at 27 sites for each vinestock. Above the upper

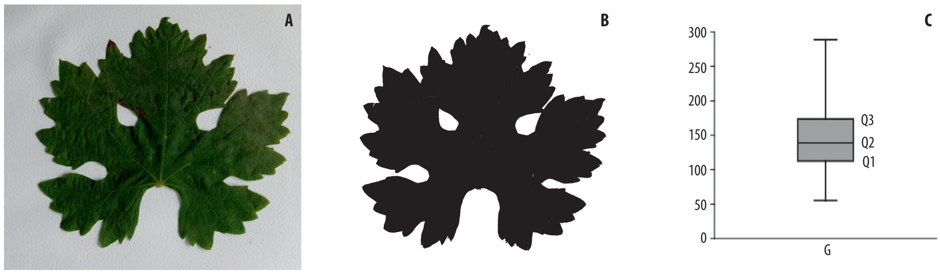


Fig. 5. Determination of leaf area. a = original image, b = binary image, c = results in box diagram, where Q_1 = 112.88; Q_2 = 138.78; Q_3 = 172.07 cm

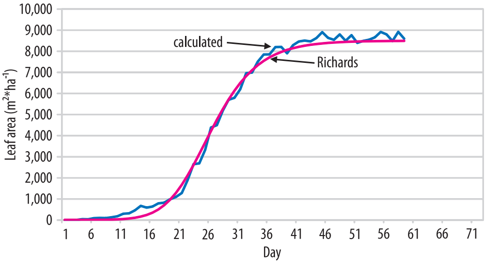


Fig. 6. Estimated growth of leaf area per hectare over 60 days (from 27 April 2019 to 27 June 2019) (blue, based on image analysis and calculations) compared to the Richards' trend function (Richards, F.J. 1959) (purple)

cluster level 10–12 leaf storeys and 0.18 m^2 leaf area per stock are optimal. The estimation of biomass production also relies on cluster thinning. 10–50 per cent of clusters are removed to reduce yield and increase average cluster mass. Lower clusters have higher sugar and lower acid contents. In premium vineyards not more than 1.2 kg yield per stock (or 8.5 t ha^{-1}) is permitted. In the experimental plot this value is usually 0.8 kg per stock. Matthiasson, S. (2013) claims that in cooler regions if half of the berries are removed, sugar content can rise by 10–20 per cent and alcohol content potentially by 11–13 per cent, which makes a great difference in wine style. Similar observations are made in Hungarian vinicultural literature (see Jakab, G. *et al*. 2013).

Leaf biomass

The C and N contents of leaf biomass were determined in several steps *(Table 1)*. Plant density, the number of shoots preserved and the leaves left on shoots were taken into account during calculations. Three quartile values have been selected from the distribution of leaf area. The most common parameter value was taken into account.

Soil carbon sequestration

For the soil balanced C/N ratios were observed. The difference between total C and TOC is Total Inorganic C (TIC) *(Figure 7)*. For C sequestration organic C-forms are of the greatest importance. Therefore, along with the C/N ratio, C_{carb}/N, TOC/N and TIC were also represented. Thus, *Figure 7* shows the total specific C and N reserves in soil. Optimal soil C/N ratio is 20–25. Although to enhance carbon sequestration the amounts of organic C-forms has to be increased, the growth of N has to keep pace with that of C. Higher N levels, however, are not desirable for the production of premium-quality grape and wine.

For soil C and N laboratory analyses showed the following values: C_{total} is 25 g kg^{-1}, N_{total} is 1 g kg^{-1}. Calculated for 1 ha this means 107 kg C and 4.0 kg N.

Since yields are rather strictly regulated, we calculated with average parameter values for minimum and maximum yields *(Figure 8)*.

Soil greenhouse gas fluxes

Yearly mean of CH_4, CO_2 and N_2O fluxes were estimated from the results of 51 sam-

Table 1. Input data for biomass estimation

Parameter	Data		
Number of vinestocks, pcs ha^{-1}	7,200 version 1	version 2	
Shoot, pcs $stock^{-1}$	6 min.	7 average	– max.
Number of leaves, pcs $stock^{-1}$	14 (Q_1)	18 (Q_2)	22 $Q_3)$
Leaf area, cm^2	112 C	138 N	172 C/N
Contents at blossom, % (SD) Contents at harvest, % (SD)	43.65 (0.62) 43.07 (0.63)	3.95 (0.24) 1.92 (0.25)	11.11 (0.59 23.04 (3.09)
	C	N	C/N
Dry weight at blossom, kg ha^{-1} Dry weight at harvest, kg ha^{-1}	417.73 272.04	47.80 12.13	– –

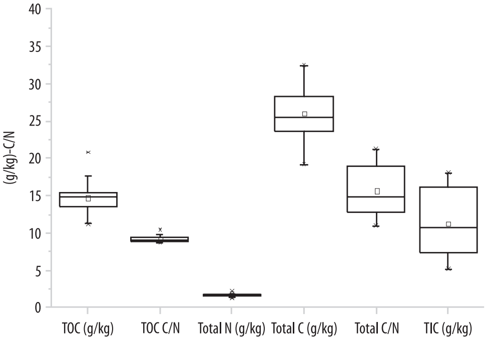
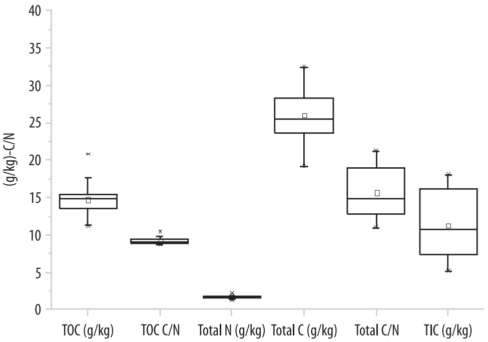


Fig. 7 TOC, TOC/N, total N, total C, total C/N ratio and TIC in in situ soil samples



Grape yield		C	N
kg ha^{-1}	kg stock^{-1}	kg ha^{-1}	kg ha^{-1}
8,500.00	1.20	3,479.05	53.29
5,760.00	0.80	2,357.62	36.11

Fig. 8. C/N ratio in grape yield (%), and C and N amounts per hectare

plings and measurements *(Figure 9).* As fluxes were practically negligible below soil temperature of 5 °C, sampling frequency was sparse during late fall, winter and early spring. The yearly mean fluxes were calculated taking into account the difference of sampling frequency between the cold and warm periods by weighting the data. Average emissions of carbon dioxide (by heterotrophic and autotrophic soil exhalation) and nitrous oxide were 2.83 t C ha^{-1} yr^{-1} and 0.41 kg N ha^{-1} yr^{-1}, respectively. Depending on anaerobic or aerobic conditions, soil was both a source or a sink of CH_4 and the sign of fluxes changed accordingly, with an average deposition rate of –0.81 C ha^{-1} yr^{-1}.

Soil erosion on medium term

Data on erosion require careful interpretation. Findings confirmed that the rate of erosion is higher in alleys than under vinestocks. In organic farming herbaceous (grass) cover crops are applied to reduce erosion. Erosion was more rapid in alleys which were ploughed for providing control plots within the frame of the Diverfarming project.

Soil erosion data are available for two years of experimentation. The rate of soil erosion from the area covered with grass mixture was 54 kg ha^{-1} y^{-1}. The soil deposit had a high organic matter content (organic C up to ca 38 g kg^{-1} – *Figure 10*) as the lightest parts (fragmented plant remains) were washed down first. Total carbonate content was identical with that of in situ soil, but showed a wide range (see *Figure 10*). (It is a good opportunity to calculate enrichment ratio for the sediment.)

In the course of soil detachment the loamy topsoil is saturated and disintegrates and its grain size distribution becomes bimodal. The complicated process is influenced by cultivation and soil erodibility *(Figure 11).*

Intensive rainfall events are rather infrequent, only occur once in four or five years, when the corresponding soil removal could several fold exceed the values measured in the present experiment. In the summary table *(Table 2)* calculated values are extended to 5 years and also to 30 years, i.e. the approximate life cycle of the grapevine.

Conclusions

1. Camouflage cameras were successfully applied for crop growth monitoring. The process of image segmentation, however, could not be fully automated as the colour composition of the intercrops is highly variable. The discrepancy between real biomass growth

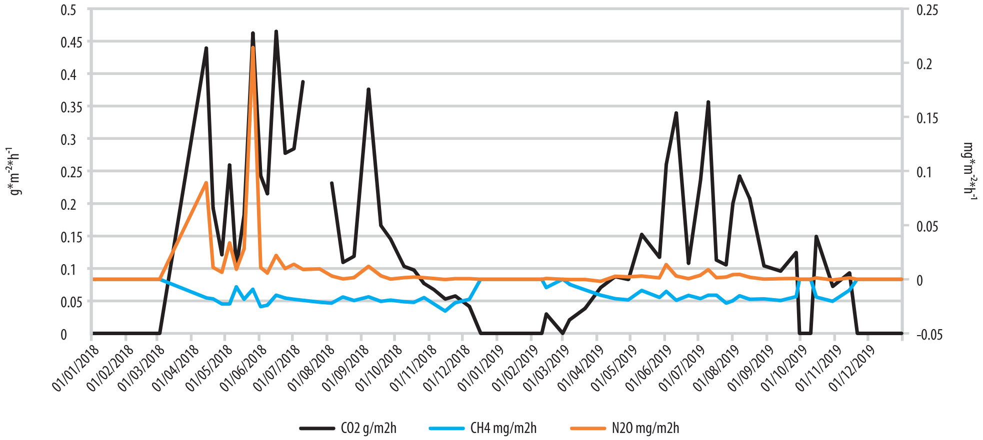


Fig. 9. Seasonal trend of soil fuxes of carbon dioxide (g m^{-2}h^{-1}), methane and nitrous oxide (mg m^{-2}h^{-1}) 2018–2019.

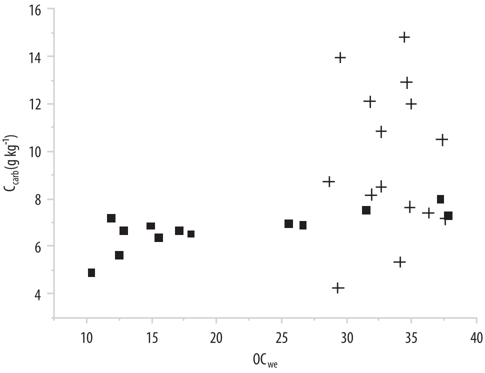


Fig. 10. Relationships between humus C (OC$_{we}$) and carbonate C (C$_{carb}$) in in situ soil (+) and eroded soil deposit (▪) (by Dezső, J.)

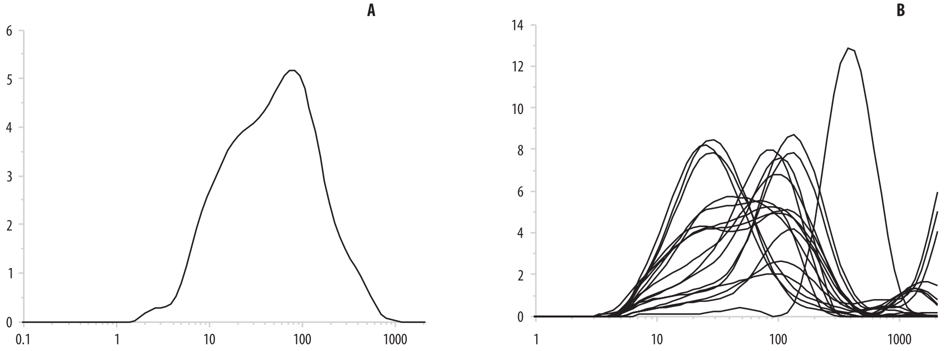


Fig. 11. Types of grain size distribution in the experimental: for *in situ* soil (a) and for soil deposits in traps (b)

Table 2. Biomass, C and N content estimations of grapevine organs compared to those of soils

Biomass	in/out	1 year			5 years		30 years	
		Dry weight	C	N	C	N	C	N
	+/–	kg ha^{-1}						
Leaf	+	957.00	417.73	17.88	2,088.65	89.40	12,531.90	536.40
Steam	–	3,657.00	1,219.96	12.78	6,099.8	63.90	36,598.80	383.40
Grape	–	713.00	291.83	4.46	1,459.15	22.30	8,754.90	133.80
Intercrop above-ground biomass	+	823.00	311.09	18.10	1,555.45	90.50	9,332.70	543.00
Eroded material*	–	54.00	2.06	0.05	10.30	0.25	61.80	1.50
Intercrop below-ground biomass	+	139.00	39.31	1.40	196.55	7.00	982.75	350.00
Soil (0–30 cm)	×	4,290,000	107,250	4,290	×	×	×	×
Total	–	*-2,451*	*-745.72*	*20.09*	*-3,728.60*	*100.45*	*-22,568.15*	*595.70*

*Intercropped alleys.

and the results of image analysis (error) can amount to 30–40 per cent. In the course of the growing season LAI changes respond to phytotechnological interventions. LAI estimation from counting collected leaves provided a normal statistical distribution. LAI and biomass growth can be modelled by the Richards' trend function (in accordance with Zeide, B. 1993). Biomass growth data were evaluated in comparison with net photosynthesis rates and soil greenhouse gas emissions.

2. The removal of cut shoots promotes the maintenance of optimal C/N ratios (around 25 to 1) in the soil. On medium term, the removal or recycling of the biomass produced by pruning and hedging as well as the mowing of cover crops and fallen leaves significantly influence C and N recharge of the soil. Residual biomass could make part of the manure superfluous and this could improve the efficiency of low-input technologies on the long run.

Vineyards play an important part in C sequestration to mitigate global climate change. Any rise in soil C content, however, would require increased N reserves, but this is not desirable in quality wine production. The cut shoots of high C/N ratio left on the ground would decompose slowly and upset the balance in the soil. In the future the boundary conditions of cultivation should be sought which satisfy the demands of quality grape and wine production parallel with reduced greenhouse gas emission and enhanced carbon sequestration in soils (Jackson, D.I. and Lombard, P.B. 1993).

3. Soil and nutrient losses from the alleys by erosion are negligible on the short run. The grain size distribution of the eroded soil is bimodal and its TOC is one and a half fold higher than the original TOC. Total carbonate contents show a wide range.

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Adaptation of land use based on the assessment of inundation risk in the Kapos Valley, Southwest Hungary

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Abstract

Complex river rehabilitation/restoration projects devote equal attention to the improvement of hydromorphological conditions and the neighbouring floodplain environment. Since land use exerts a heavy control on the hydrological cycle of floodplains, land use optimization is a central task in floodplain rehabilitation. In floodplains where large surfaces are temporarily inundated, the optimal allocation of land use classes involves the preservation of wetlands, maintenance of grasslands (meadows and pastures) and forests, and the restriction of arable land to higher ground with the lowest inundation hazard. The detailed mapping of land use against the distribution of soil types and fluvial landforms provides a solid basis for land use optimization. Rehabilitation design is presented in the paper on the example of the Kapos Valley, where inundations in the wet year of 2010 caused great damage to agricultural crops and efforts are directed to better water management (excess water reduction and floodwater retention) on the floodplain. Land use conversions, which are less expensive and easier to implement, are preferred to structural (engineering) solutions.

Keywords: floodplain rehabilitation, hydromorphology, paleochannels, peat bogs, Histosols, land use change, Kapos River

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Introduction

The deterioration of the hydromorphological properties of river channels and riparian environments in Europe, which is a long-term consequence of river regulation measures (Petts, G.E. *et al.* 1989), a type of land degradation (Kertész, Á. and Křeček, J. 2019), calls for restoration measures in the case of the majority of rivers (Tockner, K. and Stanford, J.A. 2002). Now experts agree that – in addition to the hydromorphology of river channels (Maddock, I. 1999) – rehabilitation should also extend to floodplain conditions (Brierley, G.J. and Fryirs, K.A. 2008; GWP-WMO 2012). The motives of joint river and floodplain restoration include (Wheaton, J.M. *et al.* 2015):

- aquatic and riparian ecosystem/habitat restoration,
- flood control and floodwater retention,
- floodplain reconnection,
- bank protection through planting arboreal vegetation,
- sediment management,
- improvement of water quality, aesthetic appearance and recreation opportunities.

From a geomorphological point of view, improving channel-floodplain connectivity is a key issue in any rehabilitation project (Dezső, J. *et al.* 2019). This is a precondition to maintain or enhance biodiversity, produc-

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tivity, lowering and retarding flood wave peaks, reducing nutrient loads, improving water quality, trapping sediment, promoting groundwater recharge and other ecosystem services (Holmes, N.T.H. 1998).

Worldwide research for the scientific foundation and solution of the problems of river channel and floodplain restoration/rehabilitation has produced a wealth of books and papers written by geomorphologists, hydrologists, engineers, ecologists and their joint teams over the recent decades (Nunnally, N.R. 1978; National Research Council 1992; Fischer, K.J. 1994; Sear, D. 1994; Kondolf, G.M. and Micheli, E.R. 1995; Hey, D.L. and Philippi, N.S. 1995; Brookes, A. 1996; Brookes, A. and Shields, F.D. Jr. 1996; Fennessy, M.S. and Cronk, J.K. 1997; Kauffman, J.B. and Beschta, R.L. 1997; Macdonald, K.B. and Weinmann, F. 1997; FISRW 1998; Theiling, Ch. 1998; U.S. Department of Commerce 1998; Wissmar, R.C. and Beschta, R.L. 1998; Tockner, K. *et al.* 1999; Downs, P. and Thorne, C.R. 2000; Zöckler, C. 2000; ECRR 2001; Bratrich, C. *et al.* 2002; Buijse, A.D. *et al.* 2002; Clarke, S.J. *et al.* 2003; Hulse, D. and Gregory, S. 2004; Hohausova, E. and Jurajda, P. 2005; Larsen, E.W. *et al.* 2006; Newson, M.D. and Large, A.R.G. 2006; Kline, M. 2007; Dworak, T. 2008; Schneider, E. 2010; WWF International 2010; Roni, P. and Beechie, T. 2013; Guerrin, J. 2014; Kiedrzyńska, E. *et al.* 2015; Hein, T. *et al.* 2016; Opperman, J.J. *et al.* 2017).

As a theoretical background to the issue the classical concept of 'design with nature' (McHarg, I. 1969), which also includes landscape ecological aspects, can be detected. In addition to bringing planning in harmony with natural processes, sustainability is another foremost requirement, as it is common for any other planning task. Enhancement of riparian ecosystems involves raising the value of habitats for wildlife, increasing plant or community diversity (Manci, K.M. 1989), also preserving or even increasing landscape (land use) diversity.

Today experiences on floodplain restoration are available for assessment from all parts of the world and all geographical environments (Moss, T. and Monstadt, J. 2008). Using physical (channel and floodplain morphology, sediment, flow, water quality [temperature and nutrients]) and biological indicators (fish, invertebrates, and aquatic and riparian plants), Roni, P. *et al.* (2019) evaluate the effectiveness of various floodplain restoration approaches on the basis of 180 papers. Bernhardt, E.S. *et al.* (2005) report about a comprehensive database of more than 37,000 river restoration projects of various scale across the United States. The most common objectives were to enhance water quality, manage riparian zones, improve in-stream habitat, allow fish passage, and stabilize stream banks. Only 10 per cent of project records, however, mention continuous project monitoring. This means that the ecological effectiveness of restoration activities cannot be evaluated in the majority of cases.

In the first stage the morphological floodplain and, within that, the floodway zone (i.e. the active floodplain – Bogárdi, I. and Balogh, E. 2014), allowed for inundation during floods and reserved for fluvial processes, should be delimited. The theoretical concepts to be applied in this delimitation are the geomorphic recovery potential (Brooks, A.P. and Brierley, G.J. 2004; Fryirs, K.A. and Brierley, G.J. 2016), the streamway or erodible river corridor (Piégay, H. *et al.* 2005), dyke set-back (in the German literature: *Deickrücklegung*) (Fischer, K.J. 1994), and 'room for the river' (Rohde, S. *et al.* 2006). The essence of these concepts is that free channel migration should be allowed within a zone (corridor) defined by human structures or agricultural land or any other land use types which have to be protected from bank erosion and flooding. Allowing free channel migration would spare considerable costs of water management and flood defence (Piégay, H. *et al.* 2005). The reconstruction of river history is indispensable for planning restoration, to define realistic goals of restoration actions (Brierley, G.J. *et al.* 2002; Słowik, M. 2013).

While in the floodway flood control is of decisive significance (ÖKO Rt., FÖMI and VÍZPART Kft. 2000; APFM-WMO 2017), over the protected portions of the morphological floodplain a wide range of land use classes can be present. Floodplain soils have long been used for arable farming, horticulture and grazing with increasing intensity (Posthumus, H. *et al.* 2008; Xie, H.L. *et al.* 2019), while lower-lying wetlands are valuable for water management, forestry, tourism and nature conservation purposes (WWF 2004). The broad range of floodplain land uses makes the setting of rehabilitation objectives difficult. Rehabilitation can only be successful if it is designed parallel to an incessant process of reconciliation of interests in various circles of stakeholders (see e.g. Ball, T. 2008).

Intensive agricultural use of floodplains has led to environmental problems. For instance, reclaimed peatlands have suffered deterioration through oxidation of peat and the related ground subsidence (Verhoeven, J.T.A. and Setter, T.L. 2010). In spite of their significance for landscape ecology and nature conservation, wetlands continue to be under threat of being drained and reclaimed. Agriculture is the most important non-point source of water pollution and, in addition to their hydrological role (Bullock, A. and Acreman, M.C. 2003), the buffering capacity of wetlands is vital for the efficient functioning of floodplains (Fennessy, M.S. and Cronk, J.K. 1997).

A new aspect of the optimization of floodplain land use is related to climate change (Didovets, I. *et al.* 2019; Fehér, Z.Zs. and Rakonczai, J. 2019). In addition to catchment management, river runoff, the temporal and spatial patterns of floods and droughts increasingly depend on the changing climate (Klug, H. 2016). Rainfall distribution tends to be the sole control of the regimes of rivers (like the Kapos in Southwest Hungary) which only drain low hilly regions with negligible winter snow cover. Extreme floodplain inundations closely correlate with extreme rainfall events (such as in spring and autumn of 2010). It has only recently been incorporated into water management policy that surplus water has to be stored in the floodplain to mitigate ensuing drought hazard (Somlyódy, L. 2011).

A land use analysis from nature conservation aspect (ÖKO Rt., FÖMI, VÍZPART Kft. 2000) and feasibility studies of development (Gergely E. *et al.* 2000) have considered rehabilitation needs for the Kapos catchment. These studies, however, failed to investigate all aspects of a complex transformation of the floodplain. The conclusions drawn from both our hydrogeomorphological studies (the description of embayments and gaps, valley and floodplain asymmetry, channel reconstructions) and landscape ecological assessments supply further information to the achievement of the rehabilitation goals (Lóczy, D. 2013).

Objectives

In order to identify the tasks of floodplain rehabilitation, within the complex hydromorphological and landscape ecological research project of the Kapos floodplain the following questions have been raised (Lóczy, D. 2013):

- How serious is the flood hazard in the morphological floodplain?
- How do the landscape patterns of the broader catchment, the protected floodplain (its wetlands) and the active floodplain compare with each other?
- What is the land capability of the individual floodplain sections? To what extent does the actual land use pattern provide ecosystem services? What would be an optimal land use pattern like and how to achieve it?
- How can the rehabilitation potential be rated for the Kapos floodplain?

The present paper does not cover all of these issues. It is restricted to those which are relevant for land use optimization, i.e. assessments of flood hazard, land capability, land use pattern and rehabilitation potential.

Study area

In Hungary morphological floodplains extend over 30 per cent of the county's territory. In lowland areas huge expanses of land are affected by excess water hazard (Pálfai, I. 2009).

They are vulnerable as almost 3 million people live there in 400 settlements, and 200 major industrial plants, 32 per cent of the railway network, and 15 per cent of public roads are also located in these areas (Somlyódi, L. 2011).

The medium-sized catchment of the Kapos River covers 3,295.4 km² in the South Transdanubian Hills region and the Mecsek Mountains (Lóczy, D. 2013 – *Figure 1*). The Kapos River is 112.7 km long. The morphological floodplain (without that of the tributaries) extends over 104.2 km², which makes up 3.3 per cent of the total catchment area. Consequently, runoff from the hilly parts of the catchment is concentrated in an area of limited extension.

The source of the Kapos is south of the village Kiskorpád at ca. 180 m above sea level and its confluence with the Sió Canal (the outflow of Lake Balaton to the Danube) is at 96 m elevation.

The upper Kapos catchment has a sub-atlantic climate with mean annual temperature sligthly above 10 °C and annual precipitation of 680–720 mm, while the eastern part is sub-continental (10.8–11.0 °C and 650–690 mm). The water regime shows low-water stages in August–early September and high water most often in March (caused by snowmelt in the hills) *(Table 1)*. Most of the other extremes in the regime are due to summer showers. In the embayments downstream of the town of Dombóvár rainy weather can raise groundwater levels rapidly and create extensive temporary waterlogging (Gergely, E. *et al.* 2000).

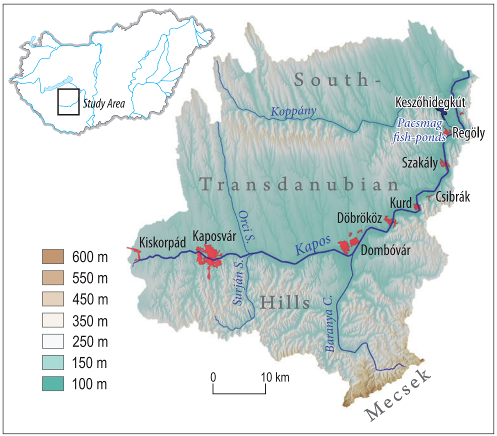

Fig. 1. Topography of the Kapos catchment.
Source: DEM with 10-metre resolution, DDVÍZIG.

As a direct corollary of regional tectonics, a remarkable asymmetry and remarkably regular alternation of floodplain constrictions (gaps) and relatively wide embayments are typical for the geomorphology of the middle and lower sections of the Kapos Valley. In the loess landscape a low-energy meandering planform evolved superimposed over landforms of coarser alluvia inherited from a high-energy Pleistocene braided river system (Słowik, M. *et al.* 2020).

At the mouths of tributary valleys small and very flat alluvial fans have accumulated. In the abandoned channels and backswamps of the embayments peat bogs formed in historical times. Poor drainage was only improved by river flow regulation (Bencze, G. 2000). The inventory of peatlands in Hungary, compiled in the 1970s, recorded former peat bogs of 851 ha area (9,140,000 m³ peat reserves) in the abandoned channels and backswamps of the Kapos and its tributaries (Dömsödi, J. 1980). Flow regulation and the accompanying floodplain drainage induced peat decomposition. Fibric Histosols (fibrous peat) have been humified to Hemic Histosols (mucky peat, muck) and, finally, to Humic Histosols (earthy peat or 'black earth'). Along the headwaters fibrous peat is found in 5–6 m thickness, while in the lower valley segment of the valley muck and humified peat beds occur in 1 m thickness (Gergely, E. *et al.* 2000). On fluvial sand deposits Fluvisols are predominant.

Methods

The steps followed in the present research were the following:

- delineation of the morphological floodplain of the Kapos River;
- reconstruction of a historical drainage pattern which had existed before river regulations started;

Table 1. Basic hydrological data on the watercourses of the Kapos system, 1995–2005

Stream	Length	Catchment	Site of gauge	Low flow	Mean flow	Median high flow	Absolute record flow
	km		river km	$m^3 s^{-1}$			
Kapos	112.7	3126.4	Kaposvár-Fészerlak, 86.0	0.055	1.724	7.54	45.5
			Kurd, 43.7	1.000	6.160	46.80	130.0
			Pincehely, 7.9	1.040	6.190	42.40	174.0
Koppány	63.6	747.1	Tamási, 14.5	0.160	1.210	30.90	77.0
Baranya Canal	38.0	606.5	Csikóstőttős, 3.2	0.120	1.830	68.00	110.0
Orci Stream	27.2	133.1	Orci, 5.1	0	0.550	27.00	27.0
Surján Stream	23.8	112.8	Szentbalázs, 4.5	0	0.290	10.30	37.0

Sources: Hydrological Yearbooks 1997–2008; Dövényi, Z. 2010

- survey and assessment of present-day land use based on remote sensing information;
- mapping floodplain soils and landforms;
- assessment of inundation hazard;
- determination of criteria for and estimation of rehabilitation potential;
- identification of needs for land conversion and design of an optimal land use pattern.

The morphological floodplain of the Kapos River was delimited using the Multiresolution Valley Bottom Flatness (MrVBF) index (Gallant, J.C. and Dowling, T.I. 2003). The algorithm identifies several assumptions referring to the flatness and low elevation of floodplains and their dependence on terrain pattern properties. The computing algorithm of the MrVBF index is compatible with the ArcInfo GRID module. The valley bottoms are delimited at a range of scales. A given site is considered to belong to valley bottom at a given scale if it is sufficiently low and flat at that scale. At each step of the procedure, in the newly generated DEM cell size increases by a factor of 3, and the slope threshold reduces by a factor of 2. (For more details see Lóczy, D. *et al.* 2012). The floodplain reconstruction based on the MrVBF index was compared with the delimitation relying on the interpretation of the Second Military Survey map sheets (from 1857–1859). The land use class 'wet meadow' approximately coincides with the floodplain, where no arable fields were cultivated at that time. Another opportunity for correction was provided by aerial photographs from the time of the 2005 flood.

Archive maps were also used to detect the positions of river channels before flow regulations. Occasionally several river branches were active in the same period. No single archive map could supply us with this information – a joint interpretation of several sources had to be employed: georeferenced map sheets of the First (1783–1784), the Second (1857–1859) and the Third Military Survey (1881–1882), a 1:10,000-scale topographic map (revised in 1999), aerial photographs of the General Directorate of Water Management (OVF) for the 2005 and 2010 floods and Google Earth maps for the identification of surfaces (paleochannels) then covered with excess water. The analyses were made in ArcGIS version 9.2 Spatial Analyst environment. In addition, paleochannels could be identified on the basis of their (peaty) soils shown on the soil map.

To prevent the transport of nutrients to water bodies, the optimal land use types along the floodplain margin are a forest zone, tree rows or grassed strips (Cronk, J.K. 1997; and Rogger, M. *et al.* 2017). The continuity of these land use classes within a 100-metre wide zone was also assessed from the land use map.

In the framework of the soil survey a total of 40 soil profiles were analyzed. The sites of soil pits and auger holes were selected on the basis of microtopography (as reflected by the DEM). Thus, the surveyed soil profiles are assumed to represent all classes of fluvial landforms in the floodplain. Soil samples were analysed in the Lovász György Physical

Geographical Laboratory of the Faculty of Sciences, University of Pécs, for grain size distribution, mineral composition, organic matter content and for type and content of carbonates. Grain size distribution was established by the Fritsch Analysette A22_32 laser equipment in the measurement range of 0.3 to 300 μm. Index values were determined according to the Hungarian standard MSZ08 0206/1-78, while water soluble salts were measured (in m/m salt%) according to the Hungarian standard MSZ08 0206/2-78. Carbonate contents were determined by Scheibler's calcimeter (German standard DIN 18 129). For the mineral composition of soil samples a Shimadzu TGA 50 thermogravi-meter was applied, which measures mass changes caused by decomposition reactions in proportion to rising temperature. Samples of 40 mg mass each were analysed at 10 °C min^{-1} heating rate.

The soil subtypes and varieties were first identified in the Hungarian genetic classification system and then referred to the WRB system. The information from point-like soil surveys was extended based on the distribution pattern of fluvial landforms. Ground Penetrating Radar (GPR) surveys were performed across abandoned Kapos channels in embayments (Słowik, M. *et al.* 2020) to reveal the internal structure of paleochannels and backswamps supplemented with 30 auger holes and corings. To estimate the age of the palaeomeanders, ^{14}C dating was carried out in the Poznań Radiocarbon Laboratory (Poland), for 20 samples of terrestrial plant macrofossils and charcoal pieces using Accelerator Mass Spectometry (AMS).

For the assessment of rehabilitation opportunities, water retention potential was used as the principal criterion. For floodplains three types of retention capacity are usually identified (Dostal, T. *et al.* 2012):

- Water retention capacity of soils – some deposits (sands) are sufficiently porous to absorb a high proportion of floodwater.
- Passive retention capacity of the floodplain – retention in backswamps, abandoned channels or other depressions of some embayments.
- Transformation effect of river channels and their floodplains – assuming that during overbank flow current velocity drops and, thus, the flood wave is decelerated.

The floodwater retention capacity of the Kapos floodplain was estimated from soil hydrological data. Maximum water capacity and storage capacity (the amount of water released from a unit volume of soil by gravitation) was rendered to the main horizons of typical soil profiles. Passive (surface water) retention capacity was estimated from the DEM and added to soil retention. Although estimations of the rate of flood peak dispersion and propagation along the river-floodplain corridor would have been useful for restoration planning, such data were not available. Therefore, flood wave deceleration was ignored in the calculations.

The classes of rehabilitation potential (mapped for the Danube by WWF International 2010 or for the Transboundary Biosphere Reserve Mura-Drava-Danube by Schwarz, U. 2013) express the degree to which connectivity between sites with high water retention potential and the main river channel can be restored. The potential varies with the floodplain segments identified (for the Kapos: Lóczy, D. *et al.* 2012). The engineering measures of floodplain restoration (Buijse, A.D. *et al.* 2002) are not treated here.

The alternatives of restoration/rehabilitation are referred into one of three groups (Smith, M.P. *et al.* 2008): 'no action', passive or active intervention *(Table 2)*. The 'no action' alternative means that the channelized river is capable of restoring its close-to-natural conditions over the long term without any human assistance. In this case the recovery potential is high. From such a strategy, however, it cannot be expected that a fully natural state is restored – not even in the very long term. Active rehabilitation aims at 'products' (creating landforms and vegetation/land use assumed to be more favourable), while passive (or non-structural) rehabilitation strives at generating processes which are expected to indirectly lead to favourable conditions later in the future (Wheaton, J.M. *et al.* 2019).

*Table 2. Comparison of the three rehabilitation approaches**

Recovery potential	General approach	Strategy	Example for intervention
High	'no action'	No intervention in the hope of natural recovery, i.e. that the river itself obliterates the consequences of minor disturbances.	Disturbances of natural origin (such as floods) lead to an equilibrium state over the long run.
Medium	passive	After implementing flood control measures, the free response of river channel is allowed and promoted.	Purchasing land in the riparian zone by the state to secure space for meander development.
Low	active	Correction of the alignment of the channelized river in order to establish a stable channel, incorporating passive procedures.	New channel alignment, bank reinforcement using natural methods but allowing space for the 'fine tuning' of flow pattern.

*Modified after Smith, M.P. *et al.* 2008.

For mapping the extent of inundation during floods, an important information for floodplain rehabilitation and land use optimization, was estimated from aerial photographs taken by the Pécs Aeroarchaeology Theca *(Photo 1)*. The distribution of inundated areas was confirmed by satellite image interpretation (Rakonczai, J. *et al.* 2003), using the image first available after the most recent major flooding of autumn 2010 (from band 6 of the Landsat-7 [ETM+] image for 24 September 2010). It shows the actual distribution of pixels where reflectance was predominantly controlled by water surface. (Reflectance was calibrated for fish-ponds in the study area.) The drainage network was superimposed

Photo 1. The Döbrököz area on an aerial photograph (May 2010) taken by the Pécs Aeroarchaeology Theca (Photo by Szabó, M.)

on the image from the Hungarian Water Management Database (although with substantial allocation error). The smoothed envelope curve embraces all 'water' pixels and provides at least an approximation potentially waterlogged areas. (This kind of reconstruction, however, only shows a partial picture of excess water inundation. Also areas with groundwater table immediately [less than 20 cm] below the surface could have been rightfully included among those stricken by excess water – Rakonczai, J. *et al.* 2003.)

The need for land conversion was identified based on a rapid land capability assessment with limited data requirement ('practical land assessment' Dömsödi, J. 2011). It only covers eight (complex) components of land quality in a weighted system (*Table 3*). According to their productivity, the genetic soil types which occur in floodplains are referred into four classes (numbers III and IV are only usable for meadow and reed economy). The assessment was supplemented with land suitability considerations, where a crucial criterion was how long the individual crops can tolerate spring–early summer inundation without severe reduction in yields (Petrasovits, I. and Balogh, J. 1975 – *Table 4*).

*Table 3. Main factors in land evaluation for practical agricultural purposes**

Number	Factor of land quality	Maximum score of agricultural site quality
1	Topography (topographic position, slope, mean depth to groundwater table, erosion and deflation hazards) Local climate (exposure)	18
2	Genetic soil type (obtained from the map 'Genetic soil types of Hungary')	9
3	Chemical properties of topsoil (pH, carbonates, salinity)	10
4	Physical soil type (specific resistance) Soil structure	9
5	Properties reducing subsoil quality (water conductivity, soil properties causing deficiency in productivity down to 150 depth)	18
6	Depth of humus layer, Soil depth	9
7	Suitability for arable and other land uses	9
8	Land capability (how many crops can be cultivated profitably)	18
Total		*100*

*Revised after Dömsödi, J. 2011.

*Table 4. Inundation tolerance of agricultural crops widely grown in Hungary measured in percentage of yield loss**

Crop	Duration of inundation, days							
	March				April			
	3	7	11	15	3	7	11	15
Winter cereals	5	15	30	50	10	25	40	70
Maize	–	–	–	–	20	80	100	100
Sunflower	–	–	–	–	10	20	50	80
Sugar-beet	10	50	100	100	10	50	90	100
	May				June			
	3	7	11	15	3	7	11	15
Winter cereals	20	40	70	100	20	50	80	100
Maize	10	50	80	100	10	40	75	100
Sunflower	15	30	80	100	20	40	80	100
Sugar-beet	10	50	90	100	10	40	90	100

*After Petrasovits, I. and Balogh, J. 1975.

Enduring waterlogging primarily precludes arable farming, while tree plantations and grazing lands are tolerant for inundation of several weeks' duration. In the case of maize even one-week duration means 80 per cent yield loss. Sunflower is also somewhat less sensitive to inundation in May.

Results and discussion

The map reconstruction of the groundplan of the Kapos paleochannel system presents an intricate low-energy anastomosing/braiding pattern with some meandering channels (*Figure* 2). There is a zone along the floodplain margin where paleochannels could not be mapped. This fact can be explained by intensive sheetwash from the neighbouring slopes onto the floodplain. The washed-down loess deposits obliterate the traces of paleochannels from the surface and also raise the elevation of the ground surface. This has important implications for land use (see later).

Creating new Kapos channel sections requires space and it is only feasible in the broadest embayments. Previous rehabilitation proposals for the Kapos floodplain (for instance, Gergely, E. *et al.* 2000) suggested channel rearrangements (primarily along the Kurd section) to reduce flood hazard. From a purely geomorphological viewpoint, the establishment of several more or less parallel, meandering channels would be an optimal solution for the restoration of a close-to-natural drainage pattern. This can be achieved through taking advantage of the infilled channels still traceable in microtopography and returning to the 19th-century regulation plans, which relied on several lateral canals running along the floodplain margins (Beszédes, J. and Herman, J. 1829). Such marginal canals could have some benefits even today:

- they conduct away the flash floods generated on tributary streams;
- dissipate the energy of floods;
- isolate the main channel from the non-point pollution of agricultural (or accident) origin (see Kronvang, B. *et al.* 2004);
- raise groundwater levels even during dry spells.

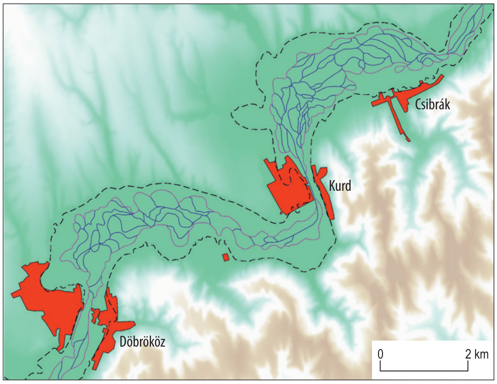

Fig. 2. Reconstruction of old Kapos channels in the Döbrököz and Kurd–Csibrák embayments (38–51 river km) for the early 19th century (drawn by Gyenizse, P. after information from military survey maps). The black dashed line indicates the boundary of the morphological floodplain and the magenta enveloping lines the channels farthest away from the valley centre line.

A detailed reconstruction of paleochannels was conducted by Słowik, M. *et al.* (2020) for the Kapos-Koppány confluence area. They discovered that single-thread meandering planform was active here since the Late Glacial. This low-energy meandering system was characterized by elongate bends with circular pools near apexes. The meanders evolved through oblique accretion, periods of cut-offs in the Late Glacial, and periods of flow discontinuation during the last 4,000 years (cf. Słowik, M. *et al.* 2020).

Are there real opportunities for dyke relocation (ECRR 2001; Clarke, S.J. *et al.* 2003) in the Kapos Valley? In the densely built-up upper (Kaposvár–Dombóvár) section any channel translocation would be difficult to implement. Downstream, however, in the broad embayments, where the floodplain rehabilitation potential is higher, they are worth of consideration. In the reach between settlements Szakály and Regöly (river km 27–24), dyke relocation seems to be an obvious and low-cost solution. Here dyke construction was unnecessary in the first place since parallel with the dyke, at ca

50 m distance, a relatively high natural levee of sand rises *(Photo 2).* The functioning of this landform of natural origin as a flood-control structure would also improve the water supply of the floodplain. To the space between the present dyke and the natural levee (which was probably also deepened as a navvy pit from where material for dyke construction was gained) the active floodplain could be extended. The bank zone being suitably landscaped, it would add to the wetlands of the Kapos Valley, store water during floods and create valuable habitats for nature conservation.

Using soil survey information, a remarkable soil water retention capacity was identified. The calculations resulted in a total maximum dynamic water capacity of 6,139,000 m^3 for the 4.45 km^2 area of embayments. Out of this amount 2,251,000 m^3 can be pumped out.

The assessment of the rehabilitation potential is primarily based on the opportunities for floodwater retention and flood risk reduction (see Lóczy, D. 2013). The results show that the rehabilitation proposals should focus on floodplain segments IV and V (*Figure 3*), where a combination of a range of interventions could improve the ecological conditions of the floodplain. Rehabilitation potential is relatively high along the reach around the confluence of the most important tributary, the Koppány (although the channelized rivers are deeply in-sized). The riverine wetlands can only be restored if groundwater levels are raised. The silt layers of low permeability in this floodplain section favours water retention after floods. (By sporadic measurements typical grain size of suspended load was found to range from 0.033 mm to 0.079 mm with a median value of 0.040 mm – cited by Bogárdi, J. 1971). However, it is doubtful whether this would be sufficient to maintain the wetlands during summer drought.

The constructed wetlands to be formed in the confluence area could be connected to the already existing Pacsmag fish-ponds, an important bird refuge, Ramsar site and Nature Reserve of 487 ha area. The constructed wetland would also increase the aesthetic value of the floodplain landscape.

Photo 2. The natural levee at Szakály with a row of poplars on the right bank of the Kapos River (Photo by Lóczy, D.)

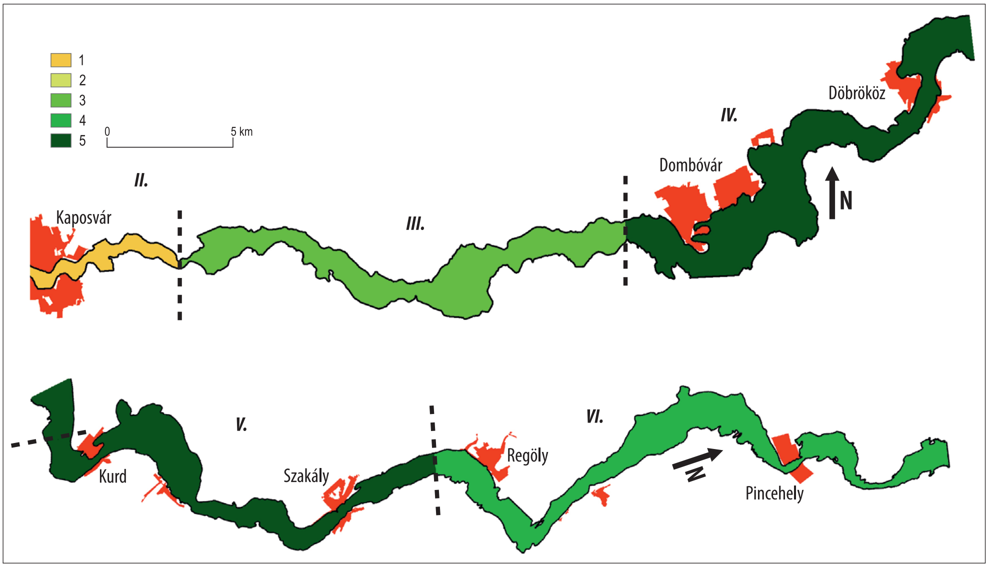

Fig. 3. Rating the rehabilitation potential of the various hydromorphological sections of the Kapos floodplain (by Lóczy, D.). The floodplain sections are identified according to Lóczy, D. (2012). II–VI = floodplain sections (river section I. has no floodplain); 1–5 = rehabilitation potentials (1 = lowest; 5 = highest one).

As far as the rationalization of land use is concerned, it has to be kept in mind that following the great river regulations and even in the period between 1960 and 1980 an important objective of water management was the increase of arable land (by 25–30 per cent) and formation of large agricultural fields (up to 300 ha area) (Bognár, Gy. 1989). Nature conservation requirements have only been observed since the late 1980s. The land use map of the Kapos floodplain *(Figure 4)* shows that forests predominant in floodplain section II are replaced by agricultural land in section III; a balance is struck between land use classes in section IV, while grasslands occupy the largest area in V and in the embayments of section VI, where forests entirely disappear. In addition, the continuity of land use classes in the floodplain sections was described quantitatively *(Table 5)*. It was found that in sections IV and V the buffer strip is continuous over almost one-third of the floodplain margin, which offers some protection against environmental pressure. Interruption of this buffer zone by arable fields have to be eliminated in the future.

Floodplain areas critical for land use have been identified relying on the findings of soil mapping and land capability assessment. There are sections, e.g. the Koppány confluence area, where flood and excess water hazard is so high that in land use planning nature conservation has absolute priority over agricultural production. Arable farming should retreat to areas where excess water hazard is low. As a general guideline, because of their relative close association, land use classes can be made correspond to the main landform units *(Table 6)*. In particular cases, however, exceptions can be made.

The land capability assessment only shows minor variations in land quality *(Table 7)*, but it is striking that in both embayments studied former peat bogs (with Eutric Histosol) are least suitable for arable farming, while the chernozem meadow soils on loess (Mollic Gleysol) favour this type of land use. This finding has to be considered in the design of land use pattern.

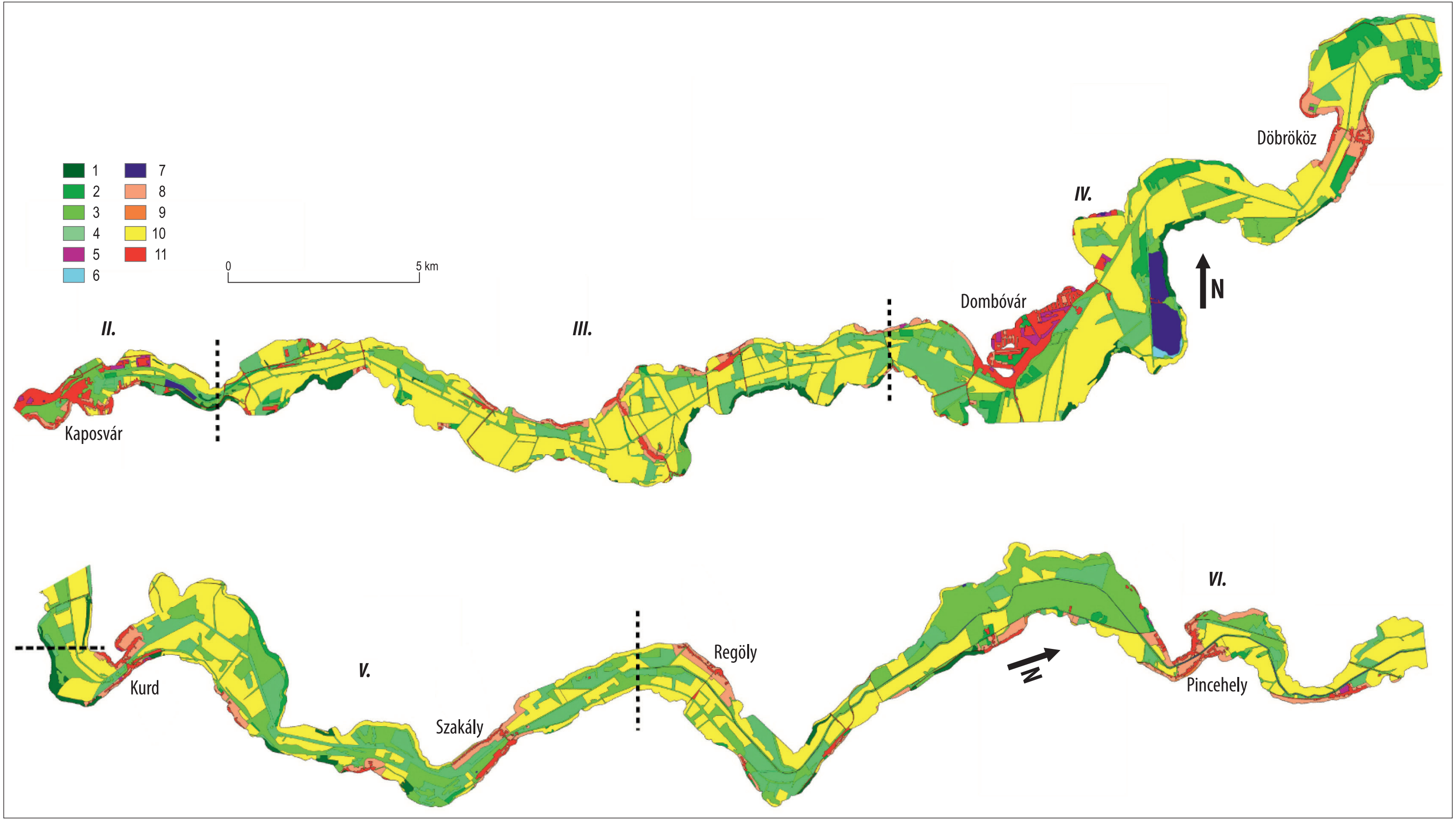

Fig. 4. Land use map of the Kapos floodplain (by Gyenizse, P.). 1 = close-to-natural forest; 2 = other forest (tree plantation); 3 = shrubs, tree rows; 4 = meadows; 5 = green area in settlement; 6 = waterlogged area, reed-bed; 7 = fish-pond; 8 = garden, orchard; 9 = vineyard; 10 = arable land; 11 = built-up area.

*Table 5. Continuity of land use in the 100-m wide strip along the river in the different floodplain segments**

Number of segment	Length of river reach, km	Area of marginal strip with bushes and trees, km^2		Ratio of strips with close-to-natural vegetation in the marginal zone	
		left-bank	right-bank	Total area, km^2	%
III	17.7	0.88	1.63	2.51	25.35
IV	19.2	1.19	2.14	3.34	30.38
V	21.3	1.12	2.07	3.19	30.31
VI	28.2	1.96	1.52	3.48	27.21

*Compiled by Lóczy, D. 2019.

Table 6. Land use proposals for floodplain landforms of different elevation

Landforms	Frequency of inundation	Proposed land use, economic activities
River terraces	Flood-free, occasional excess water from precipitation	Built-up, arable, forest, grazing land, orchard, hunting, gathering (mushrooms, forest fruits etc.)
Natural levees	Rare and short-term inundation	Orchard, horticulture, arable, forest, hunting, gathering (mushrooms, forest fruits etc.)
Low floodplain level	Irregular inundation (in 5–10-year intervals)	Pasture, meadow, forest, fishing, growing medicinal plants, hunting
Backswamps, abandoned channels	Regular (seasonal) long-term inundation	Reed-cutting, aquatic plants, waterfowl, hunting, gathering (medicinal plants, dried flowers etc.)

*Table 7. Assessment of overall land capability in the major embayments of the Kapos floodplain**

Genetic soil subtype or variety	Approximate WRB equivalent	Floodplain landforms	Main properties	Soil parent material	Soil score	
					A	B
chernozem meadow soil	Mollic Gleysol	loess slope deposit along margins	gentle slope, medium deep groundwater table	loess	70	70
’humous carbonate’ soil on sand	Mollic Arenosol, Regosols	natural levees	higher relief, deeper groundwater table	medium sand	50	52
meadow soil, meadow alluvial soil	(Fluvi-mollic) Gleysol	medium floodplain level	flat, seasonally waterlogged	fine sand	67	65
boggy meadow soil	Eutric Histosol	oxbows, backswamps	low position, waterlogged	calcareous silt with muck	48	48
earthy peat (’black earth’)	Humic Histosol	backswamps	low position, waterlogged	calcareous silty clay	58	57

*Compiled by Lóczy, D. 2019. A = Döbrököz–Csibrák embayment; B = Szakály–Keszőhidegkút embayment.

Conclusions

The proposed changes in floodplain land use could have beneficial effects even on the short run. The damage caused by flooding would be reduced and floodwater retention enhanced. Over an undeveloped and vegetated floodplain floodwater can spread out without major damage and can be stored in floodplain soils and landforms before it evaporates. The biggest challenge of successful restoration of the wetlands, however, is the raising of the groundwater levels. Silt layers of low permeability in the floodplain may reduce infiltration. However, the incised Kapos and Koppány canals drain groundwater from the underlying layers of coarse sands inherited from high-energy braided system active in Late Pleniglacial and at the beginning of the Late Glacial.

Afforestation is desirable in the higher levels of the Kapos floodplain since the roots of arboreous vegetation promote infiltration, recharge groundwater and store moisture in multi-fold higher amounts than the soils of arable fields or meadows. At the same time, the trees and herbaceous plants of the riparian zone transfer huge amounts of water from the floodplain to the atmosphere by transpiration and reduces flood wave crests. This contradicts the river engineers' view who are critical about floodplain roughness and flood protection infrastructure and claim that higher retention in a floodplain forest could lead locally to raised groundwater tables. For restoration projects a certain freeboard at dykes has to be permitted to secure local flood protection.

Through improving connectivity and water availability floodplain biodiversity could also be enhanced and the nature conservation function strengthened. In the backswamps arable farming should be replaced by meadows connected to the ecological network and gallery forests along watercourses.

Arable (or possibly organic) farming should be restricted to higher-lying, terrace-like surfaces with minimum excess water inundation hazard, favourable soil properties and water availability (ÖKO Rt., FÖMI and VÍZPART Kft. 2000). Although the marginal floodplain zone with washed-down loess veneer ('higher floodplain level') is suitable for arable farming, the intensity of cultivation has to be kept within limits even here and a buffer zone has to be excluded from intensive cultivation. In arable fields of poor productivity cereal and oil crop growing should be gradually replaced by the cultivation of or horticultural crops (e.g. horse raddish, which has some tradition in the region), while the lowest-lying tracts could be used for medicinal plants, as meadows or forests – with regard to landscape ecological consideration.

The main goals of rehabilitation should be flood control also including temporal floodwater retention (subordination of land use to flood control); improvement of landscape pattern (providing connections in all directions); increasing the effectiveness of buffer zones in order to reach better river water quality and establishing a floodplain economy in harmony with nature conservation considerations.

Future research should exploit the advantages offered by a systematic hydromorphological survey and hydraulic modelling for a more precise definition of the sites and tasks of restoration with purposes of flood control as well as the establishment of ecological corridors and buffer strips.

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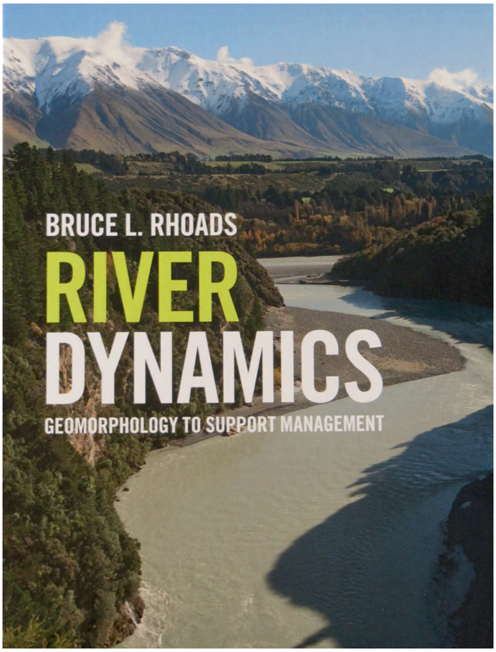
BOOK REVIEW SECTION

Rhoads, B.L.: River Dynamics: Geomorphology to Support Management. Cambridge, Cambridge University Press. 2020. 515 p.

Fluvial processes first began to dominate gomorphological literature during the period of quantitative revolution in the 1970s. The British Geomorphological Research Group estimated that the share of 'studies of fluvial character' in Great Britain jumped from 18 per cent in 1963 and to 27.7 per cent in 1975 (Gregory, K.J. 1978). The trend was similar in the United States too, where seminal papers on channel types appeared at that time. A repeated survey (Piégay, H. *et al*. 2015) found that among 7331 papers published in the five leading journals of the discipline over the period 1987 to 2009, 1717 (23%) were in fluvial geomorphology. An internet search by the author of the book reviewed here estimates a 100-fold increase in topics of fluvial geomorphology since 1980. This is another testimonial to rivers, beyond their geomorphological significance, being important components of the landscape, vital for the existence of both humans and ecosystems. The present book is a good example of the interrelationship between environmental issues and fluvial processes. The book relies on a huge number of sources, the References section consists of 73 pages! (Of course, with the customary bias in favour of United States and British sources.)



The author, Bruce L. Rhoads, professor of geography at the University of Illinois, belongs to the Midwestern school of fluvial geomorphologists, particularly of the one which was led by his recently deceased PhD supervisor, Professor William L. Graf, specialized in river investigations in desert environments. He authored and edited important textbooks with Colin E. Thorn (Rhoad, B.L. and Thorn, C.E. 1996). His research later focused on river confluences to which a separate chapter (number 12) is devoted in this book.

In the Introduction he briefly summarizes the history of fluvial geomorphology. He attempts to reconcile theories of equilibrium, geomorphological effectiveness (magnitude and frequency), landscape sensitivity and resilience – although claims that these concepts are rather difficult to test scientifically. Stability and change are governed by thresholds and the behaviour of the fluvial system is often non-linear. Examples are cited for the interpetation of general concepts in the environmental context (distinguishing between arid/semiarid and humid temperate environments).

Following the conventional structure of textbooks on the subject, Chapter 2 is concerned with overland flow processes in drainage basins. Like elsewhere, some basic processes are succinctly and clearly defined. The reader does not feel the need for a separate Glossary of terms at the end of the book. The detailed index helps the reader find these definitions. Rills and gullies are treated as landforms distinct in origin. (Although, as throughout the book, mostly US studies are cited, a single reference is also made to investigations on valley heads in the Polish Carpathians.)

Before embarking on issues of river hydrology, author inserted a chapter (no 3) on global sediment dynamics, emphasizing the leading role of rivers in global sediment flux to oceans and, consequently, in the denudation of drainage basins and continents. The limitations of the sediment delivery approach are correctly assessed. The application of cosmogenic radionuclides measurements as an alternative approach to the estimation of denudation rates and the significance of sediment tracing techniques are presented at the end of the chapter. It is interesting how laboratory experiment refined the classic model of drainage network extension and reduction and how these drainage network evolution models can be developed to landscape evolution models. Now the processing of world-wide databases allows new conclusions on the factors influencing sediment transport. For instance, it becomes evident from a series of diagrams (Figures 3.5 to 3.11) that sediment yield from a drainage basin is not a direct function of precipitation, runoff or basin area.

Relying on classic and more recent achievements in physics (fluid mechanics, open-channel hydraulics, boundary layer theory etc.), Chapter 4 summarizes the basics of flow dynamics. Although it is central among the topics of the book, it is strictly kept within limits. Even at this level of detail it is rather demanding for the reader – if he is not a mathematician or physicist.

Further fundamental processes and more physics (e.g. explanations and equations of forces like gravity, lift and drag, acting on a particle on the riverbed) come in Chapter 5 (on sediment transport). Here we get a series of precise definitions of processes. (Perhaps the only exception is the classification of channel bars, which would have been necessary to understand the explanation of meandering and braiding. This would have deserved some paragraphs in the chapter on sediment transport.) Compared to previous textbooks we encounter novel topics here, like the analysis of entrainment thresholds and particle size and pivotal angle relationships examined for sand-bed and gravel-bed rivers. Also armouring on gravel beds is seldom detailed in a book of similar content, while here the reader gets a fuller analysis based on both flume and field experiments as well as various bedload transport models. It is pointed out that, although models have been set up to predict fractional transport rates, those for sediment mixtures are yet to be tested for a diversity of conditions. Since the 1980s tracer studies support these models and help establish a virtual velocity for the particles moved in the river. The final part of Chapter 5 is concerned with the geomorphological implications of bedload transport, i.e. how it affects channel morphology and the other way round. (Of course, this topic will turn up in later chapters, too.) Author’s conclusion is that ”it is the absolute magnitude of spatial gradients in bed-material transport that govern channel change”. (Spatial gradients refer to current direction and the direction perpendicular to it.) To estimate sediment transport from surveying changes in channel parameters is even more problematic as yet and needs further research.

Chapter 6 is devoted to the assessment of a fundamental concept of 20th-century fluvial geomorphology, the magnitude and frequency of hydrological events. Is the theory still valid in the 21st century? After defining the interrelated basic terms necessary to study this issue (graded river, channel-formative event, dominant, bankfull and effective discharge), an excellent compilation in Table 6.2 summarizes the efforts to determine effective discharge values in all continents (with the notable exception of Africa). Author finally integrates the previous theories into the concept of geomorphic effectiveness. Although equilibrium thinking survives in geomorphology, he claims that ”equilibrium state is a philosophical stance” rather than a testable hypothesis. Non-linearity is also manifest in the fact that it is difficult to find a strong relationship between flood discharge and flood power (geomorphic work). Important refinements in the magnitude-frequency theory include the growing emphasis on the duration of events with high flood power which, above a threshold, can be particularly influential in channel changes as well as on antecedent conditions of formative events.

Chapter 7 answers the question whether anything new can be said about channel geometry. By all means, the difference between at-a-station and downstream hydraulic geometry is well explained and more data can be used to validate the classic equations. When downstream channel geometry is mentioned in a simplified sense, it seems necessary to introduce the algorithms of rational regime analysis, which is used for testing various hypotheses in river hydraulics. Naturally, this approach also has its limitations, which are detailed in several following chapters.

In Chapter 8 issues of channel planform, which is often identified subjectively, are treated. This is another topic which is studied excessively in fluvial geomorphological literature. The parameters applied to distinguish between meandering and braided channels (channel slope, width/depth ratio, media particle size, bank stability) are revisited in the light of recent investigations and a range of charts are presented where the two basic planform types appear distinct from each other (Figures 8.3 to 8.9). (Somewhat surprisingly, straight channels are regarded the most problematic.) The classification of multichannel (anabranching) rivers according to stream power seems to remain unsolved (anastomosing, wandering gravel-bed channels).

One of the longest of chapters, number 9, focuses on the causes and styles of meandering – another classic topic of river research. Flow oscillation and riverbed/bank instability are in the centre of theories of meander initiation. However, both theories have limitations related to the starting phase of the process, the development of alternating bar units. A difficulty of meandering river mechanism lies in the scarcity of validation of numerous laboratory experiments with field studies. Since the morphology of the individual meanders is controlled by riffle-pool sequences, the latter are described in detail – although their mathematical description is not yet possible. Neither the velocity (and shear) reversal nor the secondary flow theory provide a full and universal explanation to the maintenance of riffle-pool sequences and their contribution to curvature development. The further evolution and migration of meanders depends on sediment transport, shifting of bars, to a large extent and considerable knowledge has accumulated on these processes. Also bank erosion mechanisms are intensively investigated in connection with meander migration, lateral shifts and cutoffs included. (The reviewer would have liked to read more about the role of vegetation in bank erosion.) The development of compound meanders is a particularly intriguing issue. There is some field evidence but no theory concerning them. Similarly to other chapters, the final part summarizes the results of computer-modelling of meander evolution.

It is equally (or even more) challenging to give a short and clear answer to the question how braided channels are formed (in Chapter 10). A similarity to meandering is that most researchers agree on the role of bars in the initiation of a braided channel. The differences are presented in Figure 9.3 and 10.2. By now a wide range of laboratory experiments support theories which are based on a critical width/depth ratio to be reached. Also here an equilibrium theory is difficult to build since rapid local morphological alterations of the channel starkly contrast with long periods of overall adjustment. The concept of confluence-diffluence is used to explain bar development in braided channels. Bifurcations are due to deposition in some cases and to erosion in some others, creating seemingly minor differences in bed elevation, which, however, generate asymmetrical and dynamic conditions in the channel. Here we learn more of the role of vegetation.

Chapter 11 tackles anabranching channels, a channel planform type least studied of all so far. The morphological similarity of channels of this type masks a great variety of formative processes, basically bar stabilization into islands. Variations in channel slope, bank resistance and the density of vegetation are examined as factors producing different types of anabranching. The differences are marked among continents (Australia, Africa, South-America), but less clearly pointed out between wandering gravel-bed and anastomosing channels.

Chapter 12 is about one of author's favourite research topics: river confluences. The confluence hydrodynamic zone is interpreted as a special geomorphic environment, where helical and secondary flows are significantly modified. Sediment transport, tributary-mouth and bank-attached bar formation is largely controlled by junction angle. Proper attention is also paid to the consequences of mixing of waters with different character. All these aspects make Chapter 12 one of the most original and valuable in the book.

The study of river longitudinal profiles in Chapter 13 displays perhaps less novelty, but is equally relevant to the understanding of river dynamics. Explaining downstream fining and selective sorting of bedload, profile adjustment, knickpoint retreat etc., the chapter is useful for bachelor students, too. (This statement also applies to the introductory parts of most chapters.) This chapter summarizes the hypotheses and accumulated results on the formation of step-pool structures. The mathematical expression of their physical background is unfortunately still missing.

A modern geomorphological book could not be complete without a treatment of floodplain dynamics (Chapter 14). Overbank flow is acknowledged as essential a fluvial process as channel flow. The multifarious ecosystem services of floodplains are enumerated to underline the importance of their study. When describing deposition features, point bars and scroll bars are distinguished, the origin of ridge-and-swale topography is explained – both by deposition and erosion. Among the controls of overbank sedimentation author presents the role of suspended sediment concentration in the river on several examples. Further interesting issues are touched upon: How advective suspended sediment transport during floods producing bank-top and crevasse splays influences levee morphology? How backloading contributes to levee building? It is observed that, in addition to deposition (including the infilling of abandoned channels created by neck and chute cutoffs), erosional processes like floodplain stripping and avulsions, hardly mentioned in previous literature, also shape floodplains. Floodplain typology is based on stream power, river mechanism (planform types) and the cohesion of banks. Although the level of knowledge is far from being equal for them, Figures 14.21, 14.22, 14.24 and 14.26 allow a good visual comparison of alluvial architecture among floodplains associated with the main planform types.

Chapter 15 means to describe human impact on rivers, a theme absolutely necessary to understand the actual conditions of rivers in the 21st century. Full books have been written on the numerous indirect and direct influences exerted by human society which have completely changed the life of rivers for good. First the impacts of agriculture, then forestry and mining and finally those of urban development are investigated. Fifteen years ago a standard British undergraduate textbook about human impact on the environment (Goudie, A.S. 2006, 178–183) only mentioned river straightening, establishing of meander cutoffs and some artificial channels as deliberate interventions into fluvial systems along with alterations of sediment budget (through land use transformation) and dam and reservoir building as non-deliberate interventions. Naturally, the Rhoads book also deals with these issues, but also reflects that in the meantime the significance of further human impacts have been recognized: e.g. as agriculture involves the reduction of infiltration into the soil and of flow resistance over hillslopes, inducing rill and gully erosion, thus creating new paths for runoff. Examples of responses of rivers to land conversions and accelerated soil erosion are cited from many parts of the world. Peak discharges can also be increased by clear cutting, logging and establishing logging roads. Mining can raise sediment load considerably. Construction sites are localities where soil erosion can reach dangerous dimensions, while runoff from developed sealed surfaces often leads to destructive flash floods. The geomorphological consequences of the sediment deficite resulting from dam construction as well as planform responses to channelization are detailed based on recent reseach. Among the more indirect impacts, those of climate change take the first place. However, the interrelationships are so complicated that it is extremely difficult to predict how climate change will influence rivers, both in the short and long term.

The management tasks springing from all previous chapters are overviewed in Chapter 16. It is made clear that rivers are not simply natural resources to explit and natural hazards to mitigate, but also valuable ecological and aesthetic objects to conserve. They are not to be appreciated for their stability, but for their dynamic properties which are also of high value. The knowledge on the dynamic geomorphology of rivers and floodplains has to be incorporated into river restoration, stream naturalization and mitigation projects. To this purpose, two widely applied approaches are available: the Rosgen method and the River Styles framework. Their benefits and drawbacks are investigated. One of the last questions raised in the book is how dam removal affects rivers. Author warns of hurried action without the careful consideration of both short- and long-term impacts on river dynamics.

The book was not written for engineers. Therefore, appendices are attached to it to present power functions used in fluvial geomorphology and some sedimentological and hydrological basics.

A great merit of the book is a balanced combination of theoretical basics (BSc-level knowledge) with information on practical research problems. The rich illustrations form an integral part of the work. For a large part they are simple graphics which introduce fundamental phenomena (like Figure 6.22, which presents complex river response to base level change in a particularly clear manner), while others display measurement data from case studies in a uniform and easily interpretable format.

The most unusual feature of the book is the titles of subchapters: they are consistently formulated as special questions. The review could agree with this since it makes end-of-the chapter questions (common in textbooks) superfluous, but it is only justified if the subchapter raises a particular problem, e.g. 2.6.3 Where do channels begin? In many other cases this practice leads to changing easily palatable titles to monstrously overcomplicated ones, e.g. 7.1 How is channel geometry related to the three-dimensionality of river form?

For Hungarian master students the book may not prove an easy reading. For researchers in geomorphology, hydrology and practical experts of river management with a firm basis of scientific English, however, this is the best handbook available, an indispensable companion in their everyday work.

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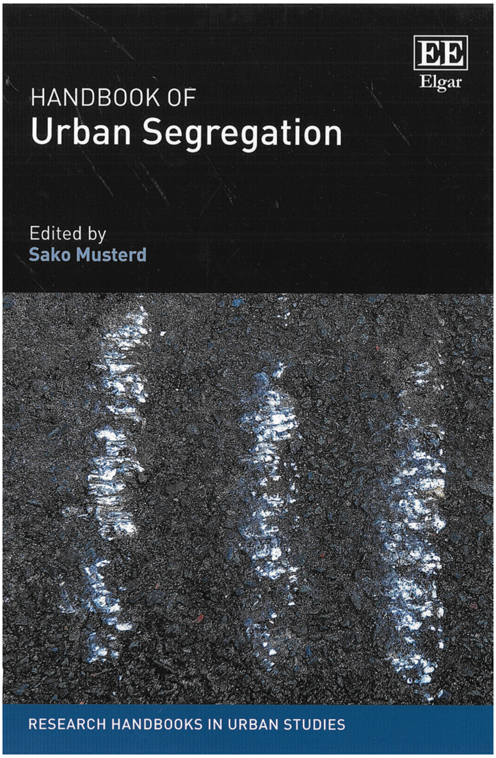
Musterd, S. (ed.): Handbook of Urban Segregation. Cheltenham–Northampton, Edward Elgar Publishing. 2020. 453 p.

Urban segregation remains a key issue in contemporary urban policy and is fiercely debated in academic circles. A range of disciplines have engaged with it, including urban geography, urban studies, urban and regional planning, political science, housing studies, urban sociology, urban design, urban economics and public policy. Reflections on segregation encompasses a number of dimensions, including demography, socio-economic distinctions (class), migrant, ethnic and race aspects, with an emphasis on the role of globalisation and the impact of various local, historically rooted urban and welfare regime contexts. Scholars with various disciplinary backgrounds from across the globe have developed a range of ideas, insights and interpretations regarding urban segregation in residential and other domains of life. A welcome contribution to this ongoing debate can be found in the *Handbook of Urban Segregation.*

The book's 24 chapters offer the reader new interpretations of familiar processes, and present recent trends in segregation studies. After Chapter 1, which is both introductory and theoretical, the book is made up of three parts: 'key segregation issues across the globe' (Chapters 2–9); 'multiple domains and dimensions of segregation' (Chapters 10–20); 'measuring and conceptualising segregation' (Chapters 21–23). The boundaries between the parts are fluid or even open, nevertheless this division helps us consider the wide variety of segregation in terms of contexts, domains, dimensions and approaches in a structured and comprehensive way. Each chapter has a historical or theoretical preface, allowing the reader to understand the nature of the question being addressed, followed by empirical research. In the epilogue (Chapter 24) Musterd, S. points to possible directions of future research into urban segregation.



Part I illustrates the variety of key segregation debates. The reader is taken to each of the earth's continents, over 10 countries and a much larger number of cities, all of which are confronted with pressing segregation issues. The contributions reveal locational specificities and institutional contexts and show that beneath the surface of known segregation aspects, new experiences are unfolding and therefore new comprehensive views on current socio-spatial divisions are needed. In this part of the volume, significant attention is given to racial segregation patterns and how, if at all, they are changing. Van Rooyen, J. and Lemanski, Ch. (Chapter 2) show, on the basis of Cape Town in South Africa, that a quarter of a century of democracy and the ending of apartheid as a system has not erased segregation. The connection identified by the authors between racial and socio-economic segregation is highly significant as it suggests that in the current era neoliberal urban governance perpetuates socio-economic and racial forms of urban segregation. Similarities with South Africa in terms of the current relation between racial and socio-economic segregation can be found in the case of São Paulo in Brazil (Chapter 3) and in US cities (Chapter 9). Marques, E. and França, D. (Chapter 3) begin with class segregation, which has a long history in São Paulo, but later they point out the increasing connection between class and race segregation, resulting in cumulative urban inequality. Jargowsky, P.A. (Chapter 9) stresses the dynamic relation between racial and economic segregation. In my opinion, these chapters show that ethno-racial identity is not the only axis of segregation, and that in cities where ethno-racial diversity is visible, socio-economic position can be a parallel or even central criterion of segregation.

In Chapters 4 and 5 the authors deal with internal changes to the welfare state type and their effects. Market-oriented reforms in the welfare regime exacerbate socio-spatial divisions. Li, Z. and Gou, F. (Chapter 4) focus their discussion of spatial inequality on the segregation of rural migrants who have settled in huge numbers around the centres of large Chinese cities. The authors emphasise the importance of market forces and institutional factors, the obstacles hindering access to urban social housing and community services, and the limited property rights available to individuals with *rural hukou* status. Randolph, B. (Chapter 5) discusses changes in the socio-spatial segregation framework in Australia after the transition to a more liberal-type regime and the subsequent increase in social inequality. The author focuses on the spatial figuration connected with the process of 'urban inversion', in which central areas of cities are transformed by gentrification and lower-class households and migrants are increasingly pushed out to suburban districts.

The next three chapters present examples from Europe showing the importance of specific local histories and contexts. Kohlbacher, J. and Reeger, U. (Chapter 6) discuss the connection between migration and segregation in Vienna. The inflow of distinct groups of migrants, from guest workers to asylum seekers, is contextualised within the city's history. Vienna's 'urban welfare policy', visible especially in housing market interventions, has prevented an increase in segregation. The example of Vienna shows that the level of segregation depends to a large extent on government policy, and globalisation has not fundamentally changed this. Energetic government policies usually restrain tendencies to increasing segregation. This is true of welfare state policies developed in Northern and Western Europe, even though their impact may be decreasing or their implementation increasingly fragmented and problematic. Oberti, M. (Chapter 8) discusses the relation between residential and school segregation in Paris. Research suggests that school segregation is greater than residential segregation and negatively impacts not only school achievement but also perceptions of inequality and even discrimination itself. Kovács, Z. (Chapter 7) draws attention to different European experiences with social and spatial divisions. The author introduces the reader to the history of Central and Eastern Europe's transformation from a state-socialist system characterised by egalitarianism, social mixing, centralised allocation and redistribution, to a system ruled by market forces. He makes the very important observation that rapid transformation may temporarily reduce spatial inequality, even while social inequality in society is proliferating. In the case of Central and Eastern Europe, segregation at micro level occurred first, then later new housing market mechanisms led to an increase in segregation levels. Similar findings were obtained from studies in which the author of this book review has participated on the relationship between social segregation, spatial isolation and changes in housing policy in Warsaw, Poland (Jaczewska, B. and Grzegorczyk, A. 2017; Grzegorczyk, A. and Jaczewska, B. 2018). Example of Central and Eastern European countries demonstrates clearly that policies which result in segregation are not always intended to do so, and similar policies may lead to different outcomes in different contextual conditions.

Part II presents the multiple domains and dimensions of segregation, and is, in my opinion, the most interesting section of the volume. The authors discuss a wide range of spheres of life that give an even more comprehensive view of segregation patterns. Two domains are highlighted first: public spaces and the quality of the environment. Madanipour, A. (Chapter 10) presents insights into the role of public space as a counterweight to social segregation and emphasises that urban development can unintentionally lead to exclusive spaces which deepen social segregation. Cucca, R. (Chapter 11) deals with the issue of environmental justice and discusses the complex relationship between quality of environment and spatial segregation. The author emphasises three very important processes: the concentration of the most deprived groups in the proximity of polluted areas; the concentration of the most affluent groups in areas with high environmental standards (garden cities) or in green innovation areas (eco-districts); and the process leading to the displacement of less affluent groups when environmental renewal is promoted in degraded areas (environmental gentrification). Such green gentrification leads to a 'green space paradox', in which greening developments are only accessible to more privileged social groups and elites. The processes presented in these two chapters are producing a new domain of segregation.

Chapters 12, 13 and 14 deal with segregation in the residential domain from a demographic perspective, albeit in combination with other dimensions of segregation. Boterman, W.R. (Chapter 12) discusses segregation among children in Amsterdam. He points out that ethnic inequalities are frequently reproduced throughout the course of a person's life. Moreover, these inequalities have a spatial dimension, as at the various stages of life households of differing ethnic groups tend to cluster in the same areas. Bråmå, Å. and Andersson, R. (Chapter 13) examine demographic segregation in the residential domain in Stockholm between 1990 and 2004, and set out to explain the changes in age and family type segregation patterns which occurred during this period. The authors argue that the declining levels of segregation noted might be attributable to the low building rates after 1990. Before 1990, due to large public housing programs which aimed to ensure homes at reasonable prices to all citizens, a firm relationship between residents' age, household type and the built environment could be observed, whereas low building rates after 1990 led to a decrease in levels of demographic segregation.

Owens, A. (Chapter 14) focuses on the residential segregation (and its spatial mapping) of households with and without children in the hundred most populated metropolitan areas in the USA. It is highly interesting that according to her research, high and low-income households with children seem to be increasingly separated across municipalities, especially between suburbs, but not between cities and suburbs.

In Chapters 15–18 the spotlight is turned towards socio-economic class, with particular reference to the middle and upper layers of society. Hanhörster, H. and Weck, S. (Chapter 15) investigate social interaction between different social groups and illustrate the important role of micro-publics in regular social encounters. Préteceille, E. and Cardo, A. (Chapter 16) present a comparative study of socio-economic segregation in Paris, São Paulo and Rio de Janeiro. The authors show that in these three urban areas the upper classes segregate themselves most, while differences in the levels of segregation are ascribed to higher levels of social inequalities in Brazil and stronger public policies and more public housing in France. The chapter is especially worthy of attention due to its well-prepared methodological introduction. Atkinson, R. and Ho, H.K. (Chapter 17) discuss the segregation practices of the very wealthy. They stress that research into the relative containment or segregation of the urban rich is important because this group has the power to shape policy responses directed towards the urban poor and those who reside in areas of poverty. This influence is exercised through lobbying for zoning restrictions, policing measures and urban housing policies intended to maintain the privileges of the wealthy while effectively reinforcing the concentration of zones of poverty outside areas inhabited by the urban rich. The geographies of the wealthiest urbanites can be seen as signalising aspects of the excessive, global and destabilising impact of global capitalist systems and their emphasis on nodal city points in which wealth is invested or realised through life in particular residential locations. The authors note that urban segregation is first a question concerning the rich, and not the poor, contrary to what is implied in much public discourse and policy. The relation between social classes is also discussed by van Gent, W. and Hochsenbach, C. (Chapter 18), but here the authors relate the waning position of the poorer sections of the population to the activities and residential behaviour of the gentrifying urban middle class.

Chapters 19 and 20 describe the vertical segregation in multi-storey housing resulting from housing quality differences between floors. Maloutas, T. (Chapter 19) shows that in Athens higher floors are preferred in terms of views, lights, fresh air and reduced noise. It comes as no surprise that the same factors are mentioned by Forrset, R., Tong, K.S. and Wand, W. (Chapter 20) when explaining the price differences in Hong Kong's high-rise buildings. The authors describe the phenomenon as the 'social stratification of air', structured by income and occupation, where the height of the buildings continues to be prized for the access it gives to clean air.

Part III of the book highlights issues that have not yet been extensively discussed in the literature but seem to be important for further research into residential segregation. Bailey, N. (Chapter 21) points out that studies of the processes behind changes in segregation remain in their 'relative infancy' and there is a clear need to develop standardised tools and software packages which will make it easier to produce comparable results from a wider range of contexts. Östh, J. and Türk, Ü. (Chapter 22) seek to model a multi-method oriented approach to how the measurement of segregation can be conducted, by comparing outputs from different multi-scale, bespoke neighbourhood methods. Walks, A. (Chapter 23) examines the origins, definitions, and measurements of the concept of the ghetto, and outlines the political implications of the debates in the scholarly literature on these areas. This chapter corresponds well to the powerful statement by Marcuse, P. (1994, 41) that 'the central problem of our societies is the division among people, and that division is increasingly reflected by walls dividing them, walls whose social weight and impact has increasingly overshadowed their physical might'.

In the epilogue (Chapter 24) Musterd, S. discusses key issues for future research on urban segregation. He emphasises that the examples shown in the present volume confirm that globalisation, neoliberal and other welfare regimes, together with historically rooted economic, social, spatial and institutional contextual conditions all continue to play a crucial role in the development of social inequality and urban segregation, but some of these forces have become overwhelming. In particular, this applies to the ongoing rise of the neoliberal intervention model. A second aspect concerns the framing of the discourse concerning inequality and segregation. Debates that currently feature in the media are based more on ideas relating to exclusion and inequality than inclusion, equality and solidarity. A shift in this emphasis could lead to a positive reframing of the discussion concerning segregation. Musterd stresses that there is much debate about 'just cities': 'cities characterised by a high decommodification, by the avoidance of a residualisation of the social housing sector, by the availability of affordable and accessible housing for all social classes and by limited social inequality; all of which result in limited spatial inequalities, and an absence of no-go or gated communities' (p. 422). I agree that this spatial justice debate is worth continuing.

An undoubted strength of the book is the fact that it presents varied urban settings from around the world, involving multiple versions of segregation that are not amenable to simple and universal explanations regarding their formative processes, their patterns and their impacts. The vast majority of the chapters have been authored by scholars with extensive research experience in urban segregation and are often based on well-known examples. At first glance I had the impression that the authors merely present the reader with processes which are already familiar. Nevertheless, after careful reading I have come to the view that the volume does, in fact, set out new interpretations of familiar processes and as such should be considered a continuation of prior research (such as Maloutas, T. and Fujita, K. 2012). I was particularly interested in the chapters dealing with issues which are not so commonly addressed in the segregation debate, like environmental justice and environmental gentrification. Of great importance in my view is the inference that the diversity of contemporary segregation patterns means that it is increasingly difficult to describe them and foresee their likely impact. International comparative research has revealed the crucial importance of confronting different contexts in understanding urban dynamics. Such physical, economic, social, cultural, and institutional contexts not only differ in the way they have developed over time, but also in how they shape contemporary realities. The studies contained in this volume attempt to find a balance between the importance of global and local factors. This allows the reader to look for the common characteristics of segregation, but also understand its specific nature in each case, in line with the assumption that a global process can manifest itself in the form of diverse local phenomena.

The book can be recommended to a wide audience, including scholars, students and all those interested in urban segregation. It will be of particular assistance to researchers in Central and Eastern European, especially if they are seeking inspiration as to ways of approaching the complexity of urban segregation. It is worth noting in this connection that Central and Eastern European countries are also experiencing an increase in urban segregation, the concentration of the middle and upper classes in gated communities, and even if the segregation indices are still quite low, this does not necessarily mean less inequality and more intense and effective contact between different groups.

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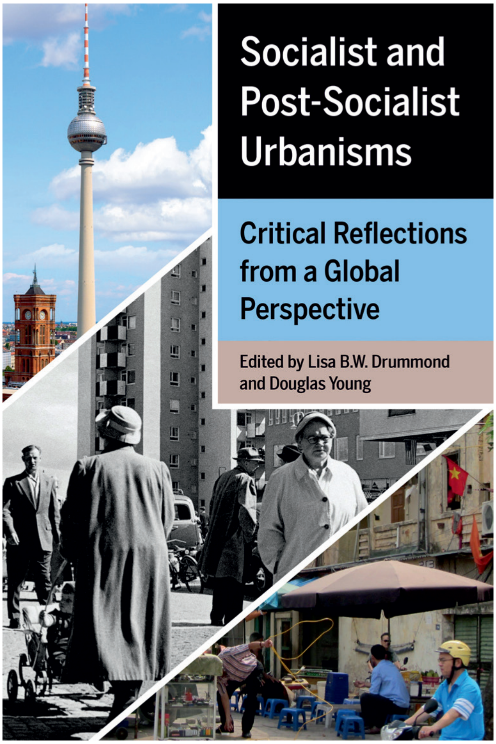
Drummond, L.B.W. and Young, D. (eds.): Socialist and Post-Socialist Urbanisms: Critical Reflections from a Global Perspective. Toronto–Buffalo–London, University of Toronto Press, 2020. 336 p.

Although it has been circa 30 years since the revolutionary changes that eventually led to the collapse of the Soviet Union and the disintegration of the Eastern Bloc, inducing fundamental reforms in 'actually existing socialist systems' worldwide, research on cities located in former socialist countries still occupies a unique niche within urban studies. On the one hand, although there was a great deal of interest in post-socialist systems in the 1990s and early 2000s from humanities and social sciences, the concept of post-socialism, in contrast to e.g. post-colonialism, has been marginalised within global theoretical discourses and remained attached to regional specialisations (Müller, M. 2019). Furthermore, as some argue, post-socialist cities are subject to double exclusion in global knowledge production, "being positioned outside mainstream urban studies but also playing an insignificant role in recent post-colonial critiques of this field" (Tuvikene, T. 2016, 133). Therefore, instead of considering these cities as anomalies in the global urban landscape, they should be promoted as unique and valuable sources of local knowledge, which are still able to significantly contribute to global urbanist discourses.



In this respect, the volume *Socialist and Post-Socialist Urbanisms: Critical Reflections from a Global Perspective* is a remarkable undertaking. The research questions addressed in this book are converged on the following issue: what is socialist about any given urban space, and what are the impacts of such perceived socialist characteristics on the contemporary evolution of these urban spaces? As such, the main aim of the editors is to offer place-specific information about the evolution of former socialist cities, providing a fascinating collection of case studies from all over the world. The volume contains 14 chapters, except the editors' introduction and conclusions, organised into three main thematic sections: housing experiences and life trajectories, planning and architecture, governance and social order. Individual chapters highlight case studies from four continents (Africa, Asia, Europe, Latin America), representing altogether 12 countries (Albania, Cambodia, China, Czechia, Ethiopia, Germany, Nicaragua, Romania, Russia, Sweden, Tajikistan, and Vietnam).

As the introduction and subsequent chapters of the book demonstrate, the contributors share Henri Lefebvre's (1991 [1974]) idea that (urban) space is a social product, which is not only a manifestation of power relations and political changes, but also an active agent and mediator in facilitating and shaping socio-spatial processes. Thus, urban space is a device to exercise social control and dominance. Not surprisingly, socialist urbanism also considered city form as a direct mode to reshape capitalist social relations and foster a socialist ideal society. As the editors of the volume suggest, socialist urbanism had at least three fundamental principles: the fate in modernist and egalitarian-collectivist ideas, industrialisation, and the education of people to create the ideal 'New Socialist Person'. These principles were conveyed by various spheres of urban life in state-socialist regimes, such as housing, architecture, and governance, as the case studies in the volume show.

The *first section* of the volume deals with housing in formerly socialist cities. The chapters in this part scrutinise how individuals and families navigated in the system of housing allocation in former state-socialist countries, and how the introduction of market reforms affected their housing careers afterwards. These studies are good examples of how general principles of socialist housing provision have been shaped by and adopted to local circumstances. Moreover, it can be learnt from the case studies that post-socialist political and socio-economic changes have made some neighbourhoods become functionally obsolete and unsuccessful, while others have proven to be more successful. This latter category includes Vällingby, a suburb near Stockholm (Larsson, B., Chapter 2), which is an exemplar of Swedish social democratic housing policy. From the narratives of Vällingby residents, it is clear that social diversity has increased significantly in the neighbourhood since the 1950s, but the original social democratic principles, such as collectivism and the concept of *'ABC town'* (work, live, centre) are still in line with the expectations and needs of the interviewed local households. Regarding less successful socialist housing developments, the reader of the book can also learn about two Vietnamese cases. The GDR-designed-and-constructed Quang Trung in Vinh City (Schwenkel, Ch., Chapter 1) and the Nguyễn Công Trứ housing complex in Hanoi (Drummond, L.B.W. and Thanh Bình, N., Chapter 3) are both *KTT*s (after the Vietnamese notion *khu tập thể*, which was based on clusters of dense apartment blocks, similar to the Soviet *mikroraion* model). The construction of these housing complexes and the allocation of their dwellings followed a socialist collectivist ideology, but under the circumstances of current market socialism, they are incompatible to the new conditions (privatisation, individualism, changing lifestyles). This is evident to authorities too, but whereas the building of these housing complexes in the state-socialist era could be carried out without community involvement and public debates, in market socialism conflicting interests among public and private actors significantly hamper any demolition or reconstruction effort. Another lesson from this chapter is that although marketisation of housing apparently created new inequalities in these cities, these can only be understood if the categorisation and differentiation logics (e.g. based on gender or cadre hierarchy) inherent in central-bureaucratic socialist housing allocation are also taken into account. A similar observation is made by Borén, T. and Gentile, M. (Chapter 4) about the Soviet housing system, investigated through the case of Leningrad (currently Sankt Petersburg, Russian Federation). Analysing a Russian woman's housing career during state-socialism, they argue that social institutions based on inhabitants' life worlds, such as housing, are rooted in informal codes rather than in the formal rules of bureaucratic central planning. Thus, even in the Soviet housing system, people could successfully influence central housing allocation to satisfy individual or collective household needs.

Chapters in *section two* (urban planning and architecture) demonstrate that post-socialist transitions are neither all-encompassing nor completed processes. On the contrary, being multi-scalar, multi-dimensional and temporally indefinite, post-socialist transformations resulted in a mixed and overlapping arrangement of socialist and post-socialist elements in the built environment of the studied cities. For example, based on a historical analysis of the spatial structure of Phnom Penh (Chapter 6), Fauveaud, G. reveals that post-socialist transitions produced political, economic, social, and territorial changes evolving at different time scales. To illustrate, transition from a centrally-planned command economy to market capitalism might be relatively fast, whereas the built environment usually changes at a slower pace. This multi-scalar character of the transition led Fauveaud to question the relevance of the post-socialist city as a coherent and universally applicable analytical concept. Similar conclusions are made by the other authors in this section. In her case study from Bucharest, Visan, L. (Chapter 8) investigates the history of the iconic buildings of the Ceausescu regime from their construction to nowadays, focusing on the Casa Republicii, later renamed to Palatul Parlamentului, and on the so-called hunger circuses, which buildings were originally intended for rationalised centrally-allocated consumption. Kip, M. and Young, D. (Chapter 9) describe the recent debates between preservationists and present-day modernisers about the regeneration of Alexanderplatz (Berlin), the epitome of East German socialist urban planning. Logan, S. (Chapter 5) takes the reader to Jižní Město ('South City'), a massive prefabricated apartment complex in Prague, good example to 1960s socialist urbanism. In all of these cases, the survival of the testimonies of socialist architecture can be observed but their development trajectories are different from each other. Some of them have become attractive targets of real estate speculation and retail capital (e.g. South City), others have been almost totally neglected by investors (e.g. Casa Radio in Bucharest), whereas in some cases new investments pose the risk to hinder the original modernist conceptions and the social purpose of these urban spaces (e.g. Alexanderplatz). To sum up, the chapters in this section well illustrate how the elements of the built environment reflect as well as facilitate ideology and societal power relations, and how these constructions are being re-evaluated, converted, or disregarded at times of transitions. Furthermore, urban space and its symbolic places are not only mediators of ideology, but also sites of resistance against dominant power relations, as can be seen at the example of Addis Ababa, Ethiopia (McClelland, J., Chapter 7).

Studies in *section three* (governance and social order) investigate the impacts of past and present governance practices on urban life, and whether path dependency or significant differences compared to the previous systems can be observed. From these chapters, one can note how different regimes (pre-socialist, collectivist socialist, market socialist, neoliberal capitalist) and different urbanist concepts and discourses (modern and post-modern, local and global, collectivist and individualist) have influenced the recent development of the selected cities. This is apparent from the case of China's Nationalized City Program (Carter, C., Chapter 10), from the analysis of socio-natural relations in Managua (Shillington, L., Chapter 12), and from the governance of urban leisure in Ho Chi Minh City (Gibert, M. and Peyvel, E., Chapter 13). It can be seen here how the elements of global urbanist discourses (e.g. sustainability, privatisation, individualised consumption) have been incorporated into official governance schemes as well as into the space producing practices of various private actors. One of the most important consequences of changing governance practices is the growing distinction between public and private spaces and separation of public and private spheres, once being blurred in many cities in the socialist era. After market reforms in these countries, new property relations and socio-spatial boundaries have been produced and marked out. This process is depicted in the chapters of this section, as an analysis of the tensions around changing territorial structures of suburban governance in Tirana shows (Mele, M. and Jonas, A.E.G., Chapter 11). Impacts of socialist governance techniques on present-day cities are also mirrored by spatial representations, as Sgibnev, W. (Chapter 14) reveals from the case of Khujand, northern Tajikistan. Analysing official and non-official maps and mapping practices from the pre-Soviet, Soviet and post-Soviet periods, he argues that mapping was always a crucial tool employed by authorities to exercise control, and emancipatory mapping practices are scarce up today. Whereas the summary of section two was ended accentuating the role of space not only as a tool for dominance but also for resistance, this last chapter in section three points to the importance of taking local circumstances and path dependencies into consideration.

According to my subjective evaluation, *Socialist and Post-Socialist Urbanisms: Critical Reflections from a Global Perspective* is a significant contribution to urbanist discourses, and it successfully responds to major challenges of research on post-socialist cities. First, critiques about the use of post-socialist city as a monolithic and totalitarian analytical concept is well documented in the international literature (e.g. Hirt, S. 2013; Ilchenko, M. and Dushkova, D. 2018). Nevertheless, the authors of the present volume recognise that certain aspects of the studied cities can be explained by the socialist past of these urban settlements, but many others cannot, thus their studies convincingly demonstrate the hybridity of post-socialist cities. Second, several scholars question the relevance of the notion of the 'post-socialist city', as it (re)produces artificial spatial and temporal boundaries, limiting the theoretical capacity of this concept (e.g. Gentile, M. 2018; Müller, M. 2019). With their strong ethnographic and historical approach, however, the authors of this volume firmly build on situated place-specific knowledge, but they also put taken-for-granted categories (e.g. informality, leisure, suburbanisation) into new perspective. In addition, they place the case-study cities into a historical perspective, instead of trying to apply post-socialism as a temporally fix category. As such, they contribute to the dynamisation and de-territorialisation of the 'post-socialist city' concept (Tuvikene, T. 2016), increasing its explanatory power in global discourses.

In conclusion, I found this book a very informative and easy-to-read one. It is richly illustrated by maps, tables, and photographs, which well-support the arguments of the authors. Most of the research behind the studies was built on qualitative methods, such as ethnographic research, interviews, participant observation, mental maps, and very powerful story-telling techniques. The research topics and the geographical locations of the case studies make the book being diverse and coherent at the same time. Therefore, I highly recommend this volume to everyone, especially to students and researchers concerned with urban studies, and to those interested in socialist and post-socialist urbanisms. I am sure that it will stimulate further research on post-socialist cities and will be frequently cited by other authors in the future.

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