Urban water budget of evaporation-optimized concrete pervious pavements

Bilan hydrique urbain de revêtements de béton poreux optimisé pour évaporation

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RÉSUMÉ

Les revêtements perméables constitués de pavés en béton poreux présentent une certaine capacité de rétention et de stockage des eaux pluviales. En comparaison avec un système de revêtement imperméable, le taux de ruissellement de surface diminue tandis que le taux de recharge de la nappe souterraine augmente. De plus, des mesures in situ montrent que les taux d'évaporation réels des revêtements optimisés pour évaporation sont supérieurs de 140 % à ceux d'un système de revêtement imperméable. En se basant sur ces mesures, les impacts de leur utilisation à grande échelle sur les taux d'évaporation urbains ont été estimés pour quatre scénarios dans la ville de Münster, à l'aide du programme GwNeu. Dans ce programme, les données observées sont combinées pour obtenir la moyenne pondérée annuelle de l'évaporation compte tenu des surfaces étanches. Les résultats d'estimation montrent des impacts considérables sur l'évapotranspiration ; par exemple, même si seuls les revêtements en béton imbriqués existants étaient remplacés, alors 630.000 m^3/a d'eau supplémentaire s'évaporeraient. De même, si 15 % supplémentaires des surfaces étanches existantes étaient remplacées, 950.000 m^3/a supplémentaires d'eau s'évaporeraient. Ceci conduirait à une augmentation du transfert d'énergie ($1{,}5 \cdot 10^{15}$ – $2{,}3 \cdot 10^{15}$ J/a) dans l'atmosphère. A l'avenir, l'utilisation étendue de revêtements perméables permettra d'atténuer l'équilibre de l'eau urbaine à l'état naturel, améliorant ainsi le climat des villes, et pourrait permettre de contrebalancer le taux croissant d'inondation.

ABSTRACT

Water-permeable pavements made of pervious concrete paving stones have a certain retention and storage capability for rainwater. Compared to an impervious pavement system the surface runoff rate decreases while the groundwater recharge rate increases. Furthermore, field measurements show that the actual evaporation rates of evaporation-optimized pavements are 240 % higher than of an impervious pavement system. Based on these measurements the impacts of large scale usage on urban evaporation rates were estimated for four scenarios in the city of Münster using the program GwNeu. In this program, observed data are combined to provide the annual area-weighted average evapotranspiration allowing for sealed surfaces. The estimation outcomes show significant impacts on evapotranspiration; for example, even if only the existing interlocking concrete pavements were replaced, then 630,000 m^3/a additional water would be evaporated. Also, if a further 15 % of the existing sealed surfaces were replaced, 950,000 m^3/a more water would be evaporated. This would lead to an increased energy transfer ($1.5 \cdot 10^{15}$ - $2.3 \cdot 10^{15}$ J/a) to the atmosphere. The extensive future use of pervious pavements can attenuate the urban water balance to the natural state; it would improve city climates, and would help counteract the increased incidence of flood events.

KEYWORDS

Evaporation, Pervious concrete, Water balance, Water-permeable paving

1 INTRODUCTION

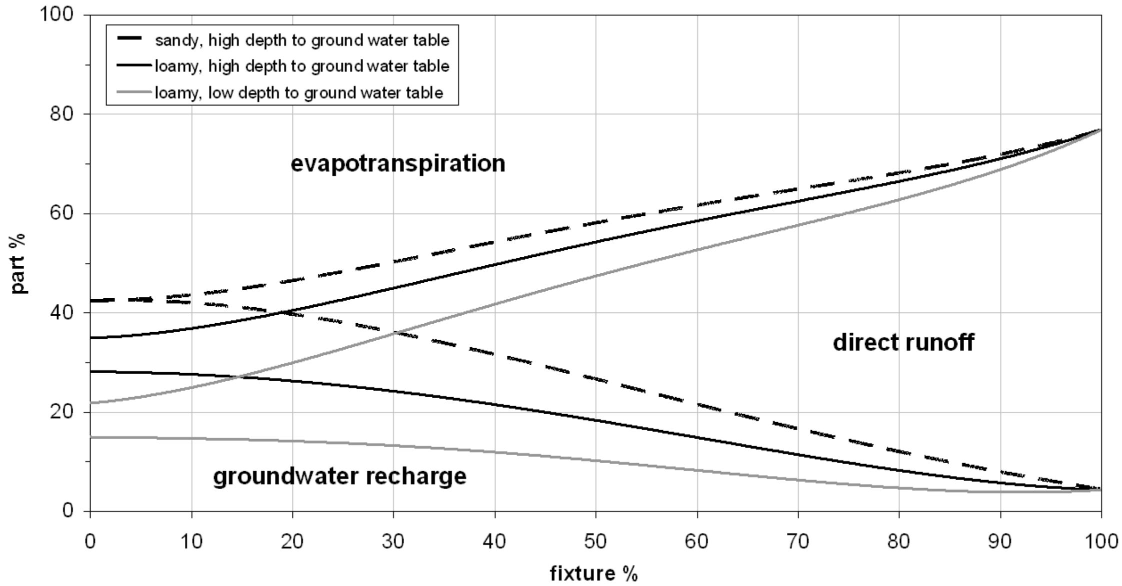
Pervious concrete is already in common use for sustainable urban drainage. The most important impact and, up to now, the main focus of the pervious concrete function is high water-permeability, i.e. precipitation water infiltrates the subsurface and therefore surface runoff is prevented. Hitherto, evaporation rates have been neglected in spite of playing an important role in the urban water balance.

Starke et al. (2010, 2011a) measured the actual evapotranspiration rates of different urban surface types in a field test using the tunnel-evaporation gauge developed by Werner (2000). The results of these evaporation measurements are the basis for the further consideration given in this study. By these measurements it was observed that a pavement consisting of grey pervious concrete paving stones has a 16 % higher evaporation rate than a pavement with impervious paving stones of the same colour (Starke et al. 2010). By a change of the colour (i.e. from grey to anthracite) a further 19 % increase of the evaporation rate was observed (Starke et al. 2011a). In the course of additional evaporation optimization processes (Göbel et al. 2013) the actual evaporation rates of these optimized paving stones are, in general, 240 % higher than those of impervious paving stones.

The deeper layers of the street pavement (and especially the sub-base) have no influence on evaporation rates. By changing the composition of the paving stone a further increase is possible, as was proven by the laboratory tests (Starke et al. 2011b) and actual field tests (Göbel et al. 2013). Through large-scale usage, the increased evaporation rates would help to mitigate flooding problems and also have a cooling effect in cities.

Within this paper the term “fixture degree” is defined as percentage of paved surfaces. These paved surfaces could be impervious roofs and roads as well as partly paved areas with interlocking concrete paving stones or gravel turf. In general the fixture degree is larger than the soil sealing degree or the degree of impervious area.

The effects on the urban water balance can be seen in Figure 1 where the relation between fixture and water balance fractions regarding to various soil types and depths to groundwater is shown. With an increase in fixture degree the evapotranspiration decreases, the direct runoff increases and at the end the ground water recharge decreases. Sandy soil with a high depth to groundwater table shows the highest impact on the groundwater recharge; loamy soil with a low depth to groundwater table shows the lowest impact. The very low groundwater recharge part for a fixture degree 100 % is related to partly paved surfaces. In area with a fixture degree under 20% the impervious surfaces area are not drained, therefore the runoff water infiltrate over the banquette in the subsoil.



mixed vegetation	allotments, gravegards and parks	residential area with detached and semi-detached housing and broad gardens	terraced and row housing, loose high-rise housing	loose large housing area, medium dense industrial and commercial area	inner city, dense large housing area, dense industrial and commercial area

Figure 1: Relation between fixture degree and water balance (evapotranspiration, direct surface runoff and groundwater recharge) under various soils and depth to groundwater table in middle Europe.

The objective of this paper is to estimate the changes for the city of Münster using four different scenarios having higher evapotranspiration rates.

2 INVESTIGATION AREA

The investigation area, the city of Münster, is about 40 km from the field test area used by Starke et al. (2010, 2011a). The city of Münster has 290,000 permanent residents and is located in the centre of the “Münsterland” area of North-Rhine Westphalia in North-West Germany. In Münster westerly winds dominate in a moderate oceanic and semi-humid climate, with a mean annual precipitation of 785 mm and a potential evaporation rate calculated after Turc (1961) of 600 mm/a. In the ‘summer’ months (March to November) the precipitation is about 409 mm. Therefore Münster and the field test area are located in the same climate zone. The calculated potential evaporation rate in the city is increased by a mean value of 5 mm (maximum 16 mm in the summer month) compared to the urban hinterland.

The ground conditions in Münster are very finely differentiated with a large number of different soil types varying over short distances. The depth to the groundwater table is also finely differentiated and in the main part of the area, the depth is > 2 m, which is suitable for water-permeable building (in Germany).

3 METHODS

The water balance, differentiated in terms of area, was drawn up for the whole investigation area using the program GwNeu (Meßer, 2010, 2011) according to Meßer (1997). The procedure of Meßer (1997) represents a modified and extended form of that according to BAGLUVA (Glugla et al. 2003) and makes use of the functionality of geo-information systems ArcView and ArcInfo from ESRI. The program is particularly suitable for urban areas (Coldewey & Messer, 1997, Göbel et al., 2004, Sendt et al., 2008) and for macro-scale examination (Neumann, 2004), and is based on the general water balance: i.e. groundwater recharge is equal to precipitation minus evapotranspiration minus direct runoff. This balance is resolved for each homogenous sub-area of the investigation area. Thus, the program, normally used for groundwater recharge calculation, has been modified for this study to address the use of evaporation-optimized pervious concrete pavements and the area-differentiated evapotranspiration estimation. The usual digital input data (mm/a) considers soil types, depth to groundwater table, land use, fixture degrees and climatic zones (i.e. normal boxes in Figure 2). By combining these areas of differentiated data the evapotranspiration is determined for each sub-area.

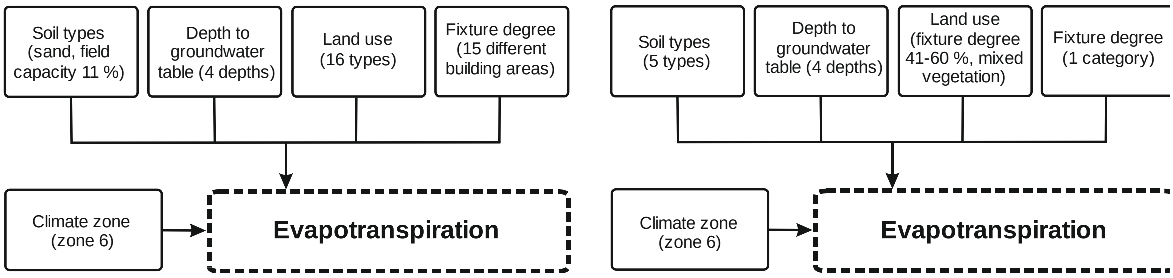


Figure 2: Scheme of the area differentiated evapotranspiration estimation using the program GwNeu (by Messer, 1997, 2011). Notes: Normal boxes: Observed data; Bold-dotted boxes: Partially estimated data, supplemented with data by Starke et al. (2010, 2011a,b). Left: Scheme of calibration; Right: Scheme of evapotranspiration estimation in Münster.

Within the calibration of the GwNeu program 15 different building areas were selected by Meßer (1997) for area-differentiated land use mapping. The housing area's fixture degree is between 10 % and 95 %. The differentiation of the trafficked area is shown in the following types of fixture:

- impervious roads of concrete or asphalt,
- areas with interlocking concrete paving stones (new),
- areas with interlocking concrete paving stones (old) and artificial paving stones (> 16 cm diameter),
- areas of mosaic and artificial paving stones (4-10 cm diameter); and
- areas with pavements made of grass pavers.

For every area it is additionally distinguished by whether it is drained to the sewer system, or not.

The fixture types of the drained trafficked areas of the 15 building areas were modified by this study in the following four scenarios:

1. Without any modification to show the representative existing residential area differentiation of Meßer (1997);
2. Water-permeable evaporation-optimized concrete pavements replace interlocking concrete pavements in a generally drained area;
3. Water-permeable evaporation-optimized concrete pavements additionally replace 15 % of drained impervious roads (concrete or asphalt) at random;
4. Water-permeable evaporation-optimized concrete pavements alternatively replace a reasonable percentage of drained impervious roads (concrete or asphalt, percentages between 30% and a complete replacement e.g. in a cemetery)

The evapotranspiration is estimated for each sub-area based on experience e.g. calibrated with lysimeter results (Meßer, 1997) and results of the field measurements (Göbel et al. 2013) (Figure 2, left). At the end of the theoretical examination of the impacts on the water balance – in particular the evapotranspiration – the results were applied on the real situation of the city of Münster.

For Münster the results of the evapotranspiration rates were modified by calibration of the program GwNeu (Meßer, 1997, 2010, 2011). This was just applied to urban areas with a fixture degree between 41 % and 60 % (Figure 2; right). The urban water balance was estimated for the same four scenarios mentioned above. Therefore, the evapotranspiration rates have to be estimated for the different existing soil types and depths to the groundwater table (i.e. 80 combinations). The results are presented in Table 1 using different units (mm/a, 10^6 m³/a). The amount of evaporated water can be converted into an estimated energy demand for evaporation in Peta-Joule units (10^{15} J). The demand per kilogram of water is 2,450 MJ for 20°C (Kuttler, 2011). In this article, it is assumed that 1 kg water is 1 L and the amount of energy is independent of water temperature.

4 RESULTS AND DISCUSSION

The results of the calibration of GwNeu for the four scenarios are shown in Figure 3. Here the fixture degree for each building area and the estimated evaporation rate are correlated for each scenario. In all scenarios the correlation coefficient R^2 shows a linear dependency of the two parameters.

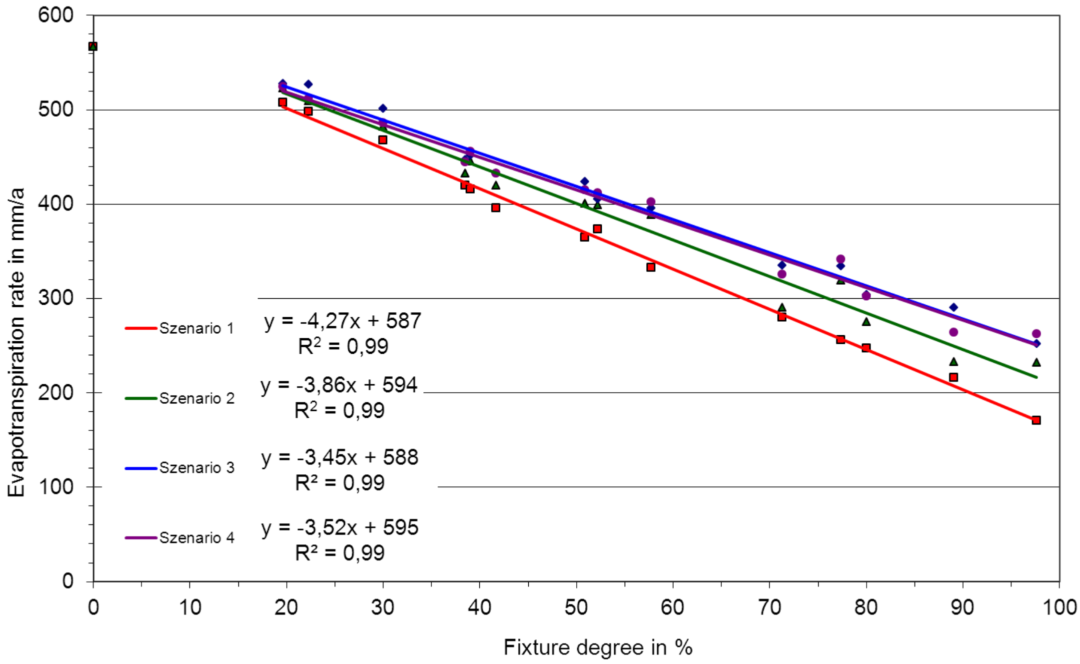


Figure 3: Results of calibration of evapotranspiration estimation in regard to their dependence on the fixture degree. Note: This example shows the calibration for eolian silt deposit (field capacity of 22 %) and a depth to the groundwater table of more than 3 m.

In Scenario 1 the original data and, therefore, the real representative existing residential area is shown. Here, low evapotranspiration rates can be seen which decrease by increasing fixture degree (502 mm/a for a 20 % fixture degree (same in the following brackets) → 374 mm/a (50 %) → 160 mm/a (100 %)). This trend can be observed in the other scenarios too. Here the starting point (20 % and about 525 mm/a to 517 mm/a evapotranspiration) is nearly the same as in Scenario 1. However the gradient (i.e. rate of decrease of evapotranspiration with increasing fixture degree) is lower. The lowest gradient is in Scenarios 3 and 4, where the evapotranspiration decreases from, respectively, 519 mm/a and 525 mm/a (at 20 %), through 416 mm/a and 419 mm/a (at 50 %), to 243 mm/a (at 100 %) in both cases. Scenario 2 takes a middle position between the three other scenarios, i.e. the evapotranspiration decreases to 401 mm/a (at 50 %) to 208 mm/a (at 100 %).

The area of Münster and the fixture degrees are shown in Figure 4. The fixture degrees were defined in 5 categories (Meßer, 1997), a categorisation that enables the shape of the city of Münster and its suburbs to be identified easily in Figure 4. The green coloured area surrounding Münster, i.e. “rural area; fixture degree 0 %, with mixed vegetation”, represents the biggest proportion of the total area (77.1 %) and is characterized by agricultural use.

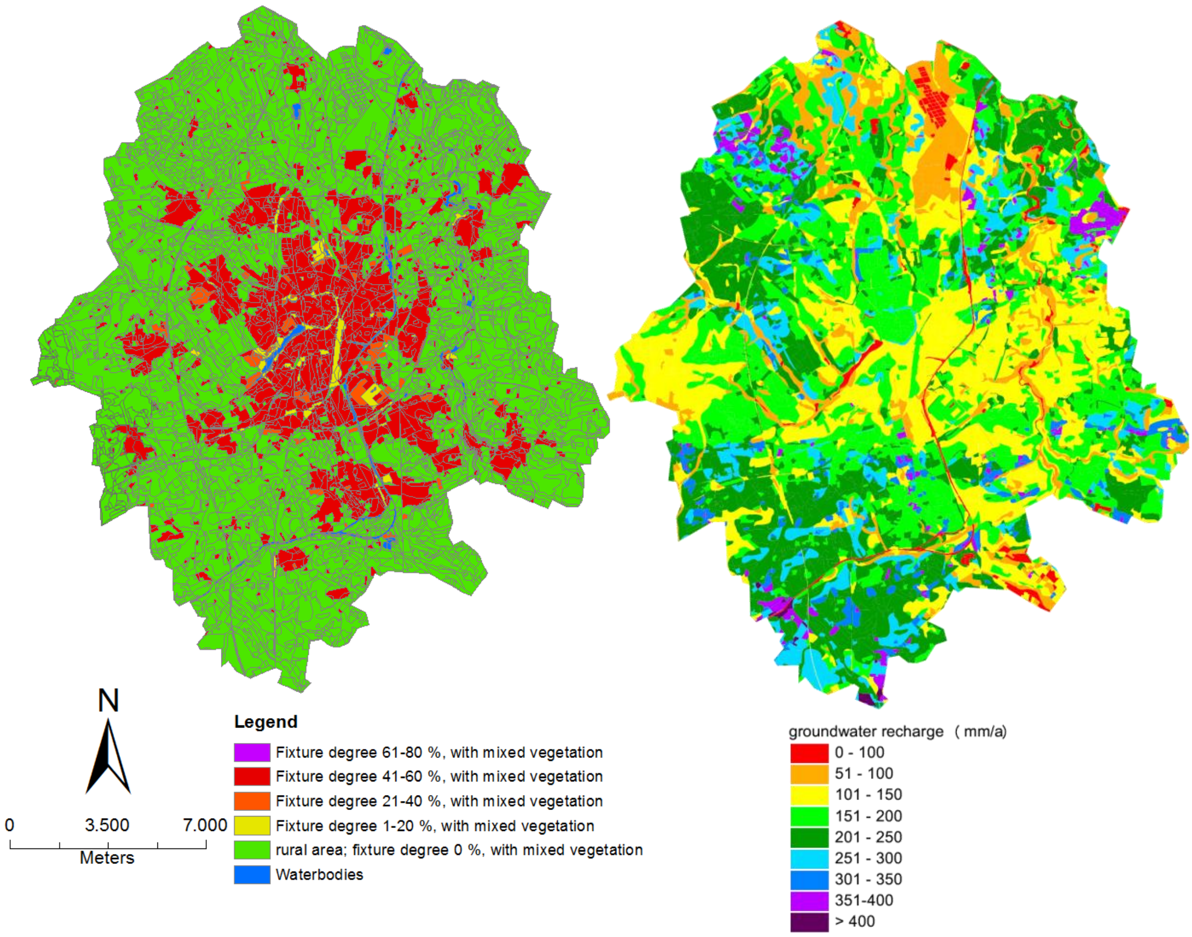


Figure 4: Map of the Administration area of the city of Münster. Note: The different colours show the categorisation (based on GwNeu) of the different fixture degree (left) and the groundwater recharge (right) .

The further categories are dominated by the category "Fixture degree 41-60 %", which covers 20.2 % of the total area. These areas are mainly residential areas (i.e. terraced and row housing and high-rise housing), but also include the inner city, industrial and commercial areas. The further categories "Fixture degree 1-20 %" which covers 1.1 % of the total area and "Fixture degree 21-40 %" covers 1.5 % of the total area, and are areas with mixed vegetation, allotments, graveyards or parks as well as residential area with detached and semi-detached housing and broad gardens.

Furthermore, there are areas which have a fixture degree of 61-80 %, but those areas comprise just the motorways to the east and big arterial roads. These areas cover just 0.1 % of the total area. Here the use of pervious concrete pavements is not possible because of the high traffic density and, partially, high driving speeds. To complete the land use, the "Waterbodies" are shown separately.

The results of the area-differentiated evapotranspiration estimation for Münster are shown in Table 1. In Münster (318.6 km^2) the representative residential area with a fixture degree of 41 – 60 % only lying in climate zones 6 has an area of 22.9 km^2. The results of the evapotranspiration estimation are based on an annual area weighted average calculation.

Table 1: Results of the area differentiated evapotranspiration estimation for Münster

Description	Area	Evapotranspiration			Energy
	(km²)	(mm/a)	(10^6 m³/a)	(m³/a)	(Δ10^{15} J/a = ΔPJ/a)
Total city of **Münster**	318.6	489.0	155.8		
Representative residential area in Münster (Fixture degree 41-60%, climate zones 5+6) (shown in Figure 4)	64.4	362.8	23.38		
Scenario 1	22.9	363.5	8.31	0	0
Scenario 2	22.9	390.4	8,94	630,000	1.5*
Scenario 3	22.9	404.4	9,26	950,000	2.3*
Scenario 4	22.9	408.4	9,35	1,040,000	2.5*

* Assumes energy needed to evaporate 1 L of water is 2,45 MJ; all values for climate zone 6

The additional amount of evaporated water based on Scenario 1 is between 630,000 m^3/a (Scenario 2) and 1,040,000 m^3/a (Scenario 4). This results in an extra energy need for evapotranspiration between 1.5 PJ/a and 2.5 PJ/a.

5 CONCLUSIONS

Starke et al. (2010, 2011a, b) and Göbel et al. (2013), as mentioned already, showed that the large-scale usage of water-permeable and evaporation-optimized concrete pavements could have a significant impact on urban evapotranspiration rates. Based on the program GwNeu, the annual evapotranspiration for the city of Münster was estimated for additional three scenarios, which are at different stages of replacement of impervious street surfaces with water-permeable concrete designs. The results have a high confidence level and show significant impacts; for example with an increase in the evapotranspiration rates of 26.9 mm/a (i.e. up to 44.9 mm/a) the urban evapotranspiration rates can be attenuated to the natural water balance in an observable way. The additional evaporated water is between 630,000 m^3/a and 1,040,000 m^3/a. The quantity of sewage water in the only sewer treatment plant in Münster could be reduced by 2,850 m³/d (ca. 5 % of Münsters treatment capacity).

These changes can be found in the water balance as well as in the energy balance. The increased evaporation results in 1.5 PJ/a up to 2.5 PJ/a extra needed energy. With higher evaporation rates, more energy is transferred from sensible heat to latent heat.

Starke et al. (2010) shows that the extra evapotranspiration takes place mainly in dry periods, several days after a rain event. During those days, the city climate is normally characterized by hot and dry air. It is possible to counteract both of those characteristics. Therefore, the large-scale usage of this approach, as proven by this balancing process, would show a significant benefit for the city of Münster in terms of both hydrology and climate.

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