# UNIVERSIDAD DE ALMERÍA

Doctorado en Ciencias Aplicadas al Medio Ambiente (Real Decreto 99/2011)

Tesis Doctoral

# EVALUACIÓN DE LA EROSIONABILIDAD EÓLICA DEL SUELO CON COLECTORES MULTIDIRECCIONALES

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Dr. Juan Luis Valenzuela Manjón-Cabeza

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TESIS DOCTORAL

# EVALUACIÓN DE LA EROSIONABILIDAD EÓLICA DEL SUELO CON COLECTORES MULTIDIRECCIONALES

## SOIL WIND ERODIBILITY EVALUATION WITH MULTIDIRECTIONAL COLLECTORS

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# UNIVERSIDAD DE ALMERÍA

## DEPARTAMENTO DE AGRONOMÍA

TESIS DOCTORAL PRESENTADA POR

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Doctorado en Ciencias Aplicadas al Medio Ambiente (Real Decreto 99/2011)

DIRIGIDA POR

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# RESUMEN

Una de las principales formas de degradación en los ecosistemas mediterráneos es la erosión. La erosión eólica del suelo toma protagonismo en las zonas áridas y semiáridas como consecuencia de sus características climáticas, junto con la ausencia de vegetación, los relieves llanos y abiertos, y la existencia de suelos sin estructura. El movimiento de las partículas del suelo, por el viento, se puede medir utilizando diferentes dispositivos. Estimamos la pérdida de suelo utilizando un túnel de viento, de diseño propio, con un escáner láser incorporado, y luego comparamos los resultados con los registros de colectores de partículas transportadas por el viento, a diferentes alturas. Los colectores pueden diferenciar entre la pérdida total y la deposición de partículas, hecho que no se puede detector, a mayor escala, en el túnel. Probamos un nuevo tipo de colector de partículas transportadas por el viento (trampas multidireccionales, MDt) en la mitad meridional de la provincia de Almería, para analizar el movimiento de partículas en siete tipologías de suelos características de la zona. Los colectores MDt son fáciles de fabricar a partir de filamentos termoplásticos con una impresora industrial 3D, mostrándose muy eficientes. Después de analizar las tasas de transporte de sedimentos y su equilibrio, encontramos que los sedimentos podían estar depositándose, en lugar de perderse, dependiendo de su dirección de origen. En las trampas superiores se capturaron diferentes tipos de materiales, que fueron estudiados por medio de difracción de rayos X, observándose, en ocasiones, sedimentos que aumentan la agregación y disminuyen la erosionabilidad eólica del suelo.

# ABSTRACT

One of the main forms of degradation in Mediterranean ecosystems is erosion. Soil wind erosion takes center stage in arid and semi-arid areas as a consequence of their climatic characteristics, together with the absence of vegetation, flat and open reliefs, and the existence of unstructured soils. The movement of soil particles, by the wind, can be measured using different devices. We estimated the soil loss using a wind tunnel, of our own design, with a built-in laser scanner, and then we compared the results with the records of collectors of particles carried by the wind, at different heights. The collectors can differentiate between the total loss and the deposition of particles, a fact that cannot be detected, on a larger scale, in the tunnel. We tested a new type of collector of particles transported by the wind (multidirectional traps, MDt) in the southern half of the province of Almería, to analyze the movement of particles in seven typologies of soils characteristic of the area. MDt collectors are easy to manufacture from thermoplastic filaments with an industrial 3D printer, proving to be very efficient. After analyzing sediment transport rates and their equilibrium, we found that sediments could be depositing, rather than being lost, depending on their direction of origin. In the upper traps, different types of materials were captured, which were studied by means of X-ray diffraction, sometimes observing sediments that increase aggregation and decrease the eolic erodibility of the soil.

# AGRADECIMIENTOS

A lo largo de este trabajo he contado con la ayuda y colaboración de muchas personas, a las que me gustaría agradecer.

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# ÍNDICE

# INTERÉS Y OBJETIVOS

# 1. INTERÉS Y OBJETIVOS

## 1.1. INTERÉS

Durante millones de años, la aridez ha sido una de las principales características de la superficie de la Tierra. Las conocidas tierras secas o drylands (ecosistemas hyperáridos, áridos, semiáridos y subhúmedos secos) ocupan en la actualidad más de un tercio de la superficie continental según el índice de aridez del Programa para el Medio Ambiente de las Naciones Unidas (PNUMA), de acuerdo con Pointing y Belnap (2012). Una población en constante crecimiento unida a acciones como el aumento de instalaciones energéticas, una mala gestión del uso del suelo, el aumento de las temperaturas y un cambio de régimen en las precipitaciones son las causantes de la degradación. Una de las principales formas de degradación en los ecosistemas mediterráneos es la erosión, ya sea, hídrica o eólica.

La erosión eólica toma protagonismo en las zonas áridas y semiáridas como consecuencia de sus características climáticas. Entre ellas, encontramos la existencia de vientos turbulentos, precipitaciones escasas y largos periodos de sequía entre precipitaciones puntuales. Todo ello, acompañado por la ausencia de vegetación, los relieves llanos y abiertos (planicies) y la existencia de suelos sin estructura (Aimar et al., 2011). Todos estos factores han despertado especial interés por la investigación en la erosión eólica debido a sus numerosos efectos negativos. Esto ha originado que un gran número de investigadores de diversas disciplinas tengan en consideración este proceso en sus áreas de estudio (McTainsh y Strong, 2007).

La importancia ambiental y agrícola en el SE español es más que conocida, tanto por su característica aridez, como por la presencia de una agricultura que ha sabido adaptarse a las variables condiciones que el desierto impone. Uno de los factores que influyen directamente en la pérdida del suelo y sobre el cuál se centra esta Tesis Doctoral es la erosión eólica, definida, según Quirantes (1987), como la pérdida selectiva, recurrente y progresiva de la capa superficial del suelo por la acción del aire. Se trata de un proceso natural, mediante el cual, el viento arranca y transporta partículas del suelo, desgastándolas, arrastrándolas y haciéndolas incidir sobre materiales y áreas.

Para comprender mejor este proceso, es necesario explicar el efecto y las consecuencias de la erosión eólica globalmente. Según diversos estudios previos, en nuestras condiciones, la erosión ocurre muy lentamente y su impacto sobre la calidad y productividad de los suelos no llega a detectarse hasta pasados varios años. Además, las prácticas de agricultura convencional, por ejemplo, el uso de fertilizantes y otros insumos agrícolas, pueden enmascarar los efectos que tiene la erosión eólica sobre la productividad (Van Den Biggelaar et al., 2001)

En estos últimos años se ha avanzado en el conocimiento de la distribución de la erosión eólica en Europa, comprobándose en determinadas áreas que la tasa de erosión por viento puede ser tan alta como la de erosión hídrica. Esto nos alerta de la necesidad de prevenir y combatir el problema, por lo que es necesario conocer la susceptibilidad del suelo. Así, la erosión viene determinada por características edáficas como: textura, contenido en material orgánica o en humedad. Los suelos con textura arenosa (sobretodo arena fina), son más erosionables, por crear estructuras edáficas inestables y por su rapidez en secarse tras la lluvia o el riego. La materia orgánica es un factor condicionante de la agregación del suelo. La humedad influye en la adhesividad entre partículas.

Por otro lado, el clima, la vegetación, la pedregosidad y las condiciones de la superficie del suelo influyen en la capacidad erosiva del viento condicionando la pérdida de productividad del suelo.

Teniendo en cuenta lo expuesto anteriormente, debemos indicar que en agronomía existen multitud de medidas que reducen la erosión del suelo, enfocadas bien, en reducir la erosividad del viento (reduciendo su velocidad) o bien, en disminuir la erosionabilidad de la superficie de los epipedones.

## 1.2. OBJETIVOS

Nuestros objetivos son estudiar la influencia del tipo de suelo en la pérdida eólica de material, en siete tipologías de suelos representativas del SE de España, utilizando diferentes métodos. Pretendemos mostrar las diferencias entre la cantidad de material del suelo erosionado por el viento, que es recogido de acuerdo a estudios tradicionales, frente una nueva técnica, utilizando colectores de partículas de diseño propio, patentados a través de la Universidad de Almería. Además, queremos comparar las diferencias cualitativas y semicuantitativas entre los minerales del suelo transportados por el viento desde suelos circundantes y sus efectos sobre las características del suelo en el que se produce su depósito.

# LOCALIZACIÓN GEOGRÁFICA Y ANTECEDENTES

# 2. LOCALIZACIÓN GEOGRÁFICA Y ANTECEDENTES

## 2.1. LOCALIZACIÓN GEOGRÁFICA

### 2.1.1. ZONA DE ESTUDIO

La provincia de Almería está ubicada entre las latitudes 37º 52’ y 36º 40’ y las longitudes 1º 37’ y 3º 07’. Es una de las provincias más montañosas del territorio español y entre sus accidentes orográficos caben destacar las Sierras de Gador, los Filabres, Alhamilla, Cabrera, Almagrera, de María y de las Estancias, sin olvidarnos de su proximidad a Sierra Nevada que se introduce por el extremo oeste de la geografía provincial. Estas sierras elevan el territorio a más de 2.000 metros de altura. La provincia de Almería cuenta con una superficie de 8.774 $km^2$; contiene un total de 103 municipios agrupándose en ocho comarcas agrarias: Los Vélez, Alto Almanzora, Bajo Almanzora, Río Nacimiento, Campo de Tabernas, Alto Andarax, Campo de Dalías y Campo de Níjar-Bajo Andarax, (Simón et al., 2005).

El área de estudio de esta Tesis Doctoral está ubicada en el centro de la mitad meridional de la provincia de Almería, (Fig. 1, 2 y 3). El clima es mediterráneo semiárido con una temperatura media anual de 18,6 ° C y precipitaciones de 248 mm. El material geológico dominante es una serie sedimentaria del Mioceno. Las comunidades de plantas naturales son arbustos nativos aislados, pero en la actualidad también hay una intensa actividad hortícola y de cultivos arbóreos. Según el Grupo de Trabajo de IUSS WRB (2015), los suelos estudiados son Anthrosol hortico ($AT_h$), Leptosol eútrico ($LP_e$), Arenosol endosálico ($AR_{sa}$), Cambisol calcárico ($CM_c$), Calcisol arídico ($CL_a$), Fluvisol gypsico ($FL_{gy}$) y Luvisol crómico ($LV_x$) (Fig. 4 y 5).

Los registros meteorológicos se tomaron de la red de estaciones meteorológicas automáticas del Instituto Andaluz de Investigación y Educación Agraria y Pesquera (IFAPA) (http://www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/servlet/FrontController), una institución de la Junta de Andalucía. En todos los casos hubo rachas de viento superiores a 24 m·s$^{-1}$.

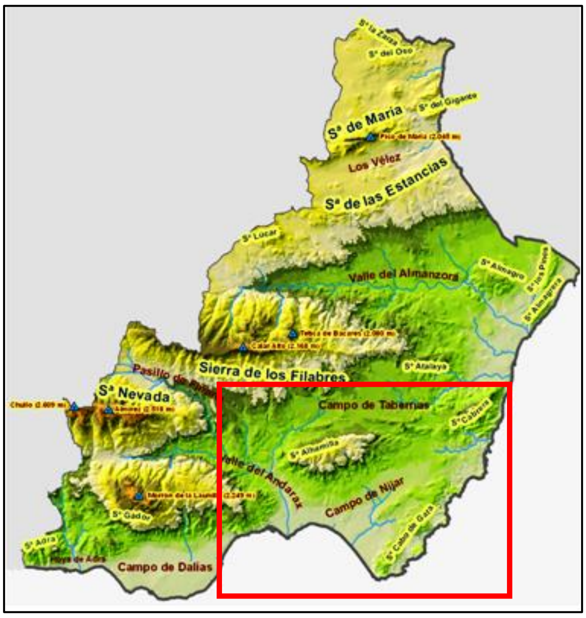


***Figura 1.*** *Mapa físico de la provincia de Almería (Castellano, 2008)*


***Figura 2.*** *Imagen de Google-Earth de la zona de studio*

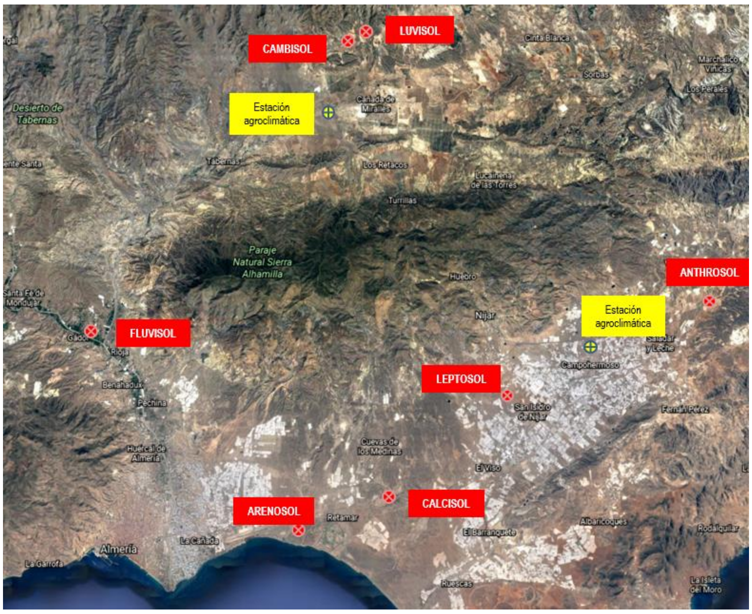


***Figura 3.*** *Imagen de Google-Earth donde se localizan los suelos estudiados y las estaciones agroclimáticas presentes*

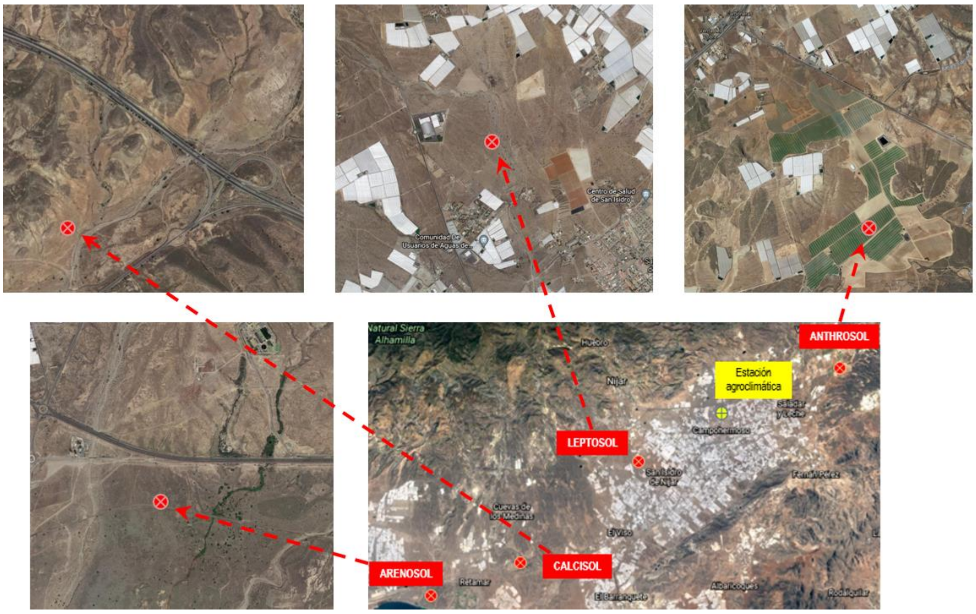


***Figura 4.*** *Localización de Anthrosol, Leptosol, Arenosol y Calcisol*

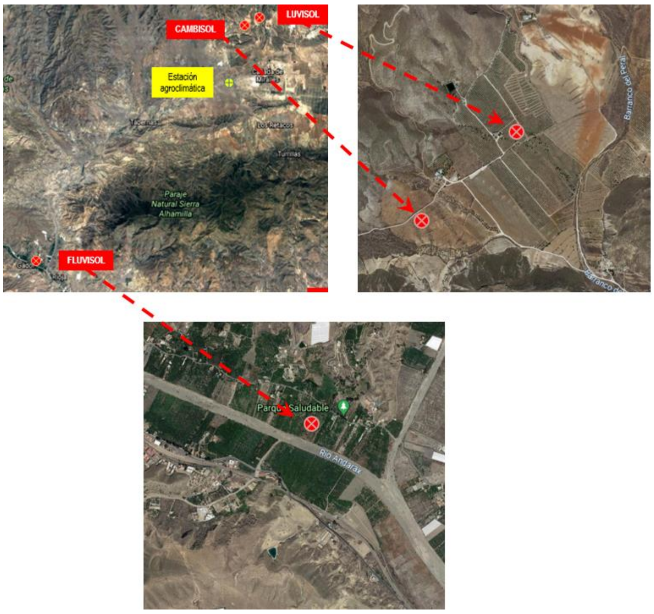


***Figura 5.*** *Localización de Cambisol, Fluvisol y Luvisol*

## 2.1.2. DESCRIPCIÓN DE LOS SUELOS DE ESTUDIO

Los suelos presentes en la zona de estudio se describen a continuación, según la Base de Referencia Mundial del Recurso Suelo, WRB (FAO, 2015).

*Anthrosol calcaric-hórtico (AT$_h$)*

Por lo general, los Antrosoles comprenden suelos que han sido profundamente modificados a través de actividades humanas, como adiciones de materiales orgánicos, desechos domésticos, riego y labranza. El material parental puede proceder de cualquier suelo modificiado mediante cultivo o adición de materiales continuos y prolongados.

*Leptosol eútrico (LP$_e$)*

Los Leptosoles generalmente son suelos muy superficiales, que suelen aparecer sobre roca continua, siendo extremadamente pedregosos. El material parental está formado por varios tipos de roca continua o materiales no consolidados con menos del 20% (en volumen) de tierra fina. Estos suelos se encuentran en particular, en áreas fuertemente erosionadas.

*Arenosol aric-eolic-endosálico ($AR_{sa}$)*

Generalmente, los Arenosoles comprenden tanto aquellos suelos desarrollados en arenas residuales, como suelos desarrollados en arenas recién depositados como dunas, playas… Aunque la mayoría de Arenosoles ocurren en regiones áridas y semiáridas, se encuentran en un amplio rango de climas, desde muy árido hasta muy húmedo y desde frío hasta cálido. Además, están muy extendidos en paisajes de fuerte inlujo eólico y ocurren tanto en superficies muy antiguas, como en geoformas muy recientes. En tierras áridas, donde la lluvia es menor de 300 mm, son predominantemente usados para pastoreo extensivo. La baja coherencia, baja capacidad de almacenar nutrientes y alta sensibilidad a la erosión son los limitantes a esta tipología en estas zonas.

*Cambisol hapli-calcárico ($CM_c$)*

Los Cambisoles son suelos que se caracterizan por tener un horizonte B de alteración. Su color es de un tono rojizo que da evidencia de esa alteración. La superficie puede poseer un mayor contenido en arcilla que el horizonte que subyace. Presenta unos materiales de textura media a fina. Según la Base de Referencia Mundial del Recurso Suelo (WRB), los Cambisoles se clasifican como suelos moderadamente desarrollados.

*Calcisol gypsi-arídico ($CL_a$)*

Son suelos cuya característica principal es que dentro de los 100 cm de profundidad, encontramos un horizonte cálcico o petrocálcico. Generalmente, han sido desarrollados a partir de materiales dendríticos; además, son lo suficiente permeables para que se haya producido el lavado de calcio en el suelo. Son suelos muy extendidos en ambientes áridos y semiáridos. Para muchos, los Calcisoles se incluyen en los suelos de desierto (Desert soils) y Takyrs.

*Fluvisol aric-gypsico ($FL_{gy}$)*

Los Fluvisoles, por lo general, son suelos profundos que presentan una topografía prácticamente llana y sin afloramientos rocosos. Estas características les convierte en suelos muy aptos para ser cultivados, aunque con un impedimento, la carencia de agua. El interés en aplicarle riegos está provocando la salinización de algunos suelos, por la sobreexplotación de los acuíferos. Estas zonas se muestran intensamente cultivadas tanto por árboles frutales de hueso y de pepita, como por hortícolas.

*Luvisol hapli-crómico ($LV_x$)*

Los Luvisoles son suelos que tienen un mayor contenido en arcilla en el subsuelo que en superficie. Esto se debe a procesos pedogenéticos de migración de arcillas. Aparecen en zonas geomorfológicas estables que han sido preservadas de procesos erosivos. Por lo general, la mayoría de los Luvisoles son fértiles y apropiados para usos agrícolas.

### 2.1.3. FACTORES FORMADORES DE LOS SUELOS

Los distintos tipos de suelos pueden ser modelados en función a factores ambientales y constitucionales como el clima, geología, relieve, vegetación y la acción antrópica.

#### 2.1.3.1. CLIMA

El clima de la provincia de Almería se define como subdesértico, mediterráneo, cálido y seco. Recibe entre 3.000 y 3.600 horas de sol al año y una nubosidad media de 35 días al año. Sus veranos son cálidos y sus inviernos templados. Además, presenta una de las zonas donde menos llueve de España, Cabo de Gata, con aproximadamente 125 mm de lluvia al año. Las temperaturas medias oscilan entre los 22ºC en verano y los 12ºC en invierno. No obstante, dadas las grandes variaciones de altitud el rango es relativamente amplio.

En cuanto a la pluviometría, si exceptuamos las zonas montañosas, las precipitaciones oscilan entre los 150-300 mm, dándose en las proximidades de Sierra Nevada casi los 650 mm (Fig. 6). Las elevadas temperaturas y las bajas precipitaciones nos llevan a largos períodos de déficit hídrico. Estas precipitaciones tan escasas son el resultado de la circulación atmosférica general del Mediterráneo. Los vientos del

Atlántico (vientos del oeste), van descargando progresivamente la mayor parte de la humedad a su paso por los numerosos relieves existentes entre la costa atlántica y Almería, llegando a ésta última prácticamente secos. Por lo tanto, las mayores precipitaciones ocurren gracias a los frentes del Mediterráneo, entre los meses de septiembre y octubre, produciendo, en ocasiones, depresiones aisladas en niveles bajos (DANA), por el choque de masas de aire frío en altura, con el aire caliente de la superficie.

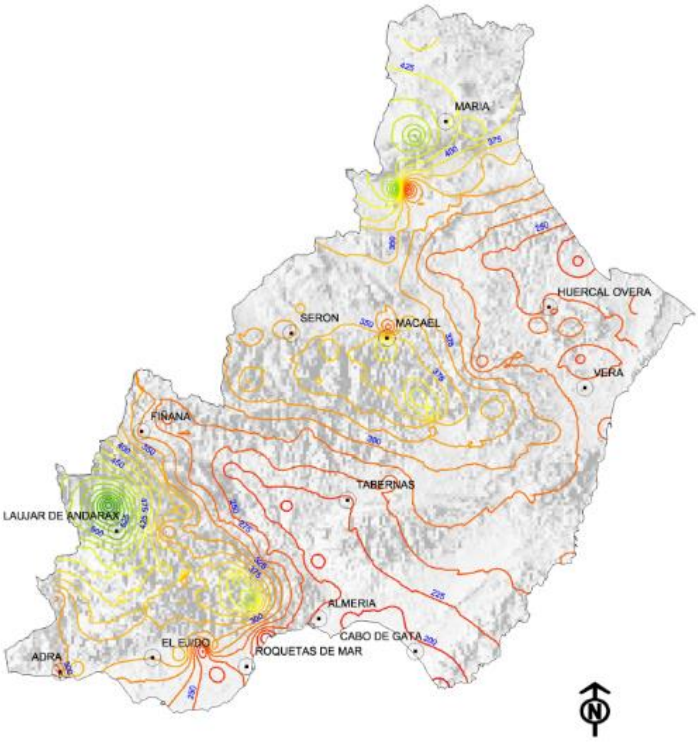


***Figura 6.*** *Precipitaciones medias de la provincia de Almería (Simón et al., 2005)*

### 2.1.3.2. GEOLOGÍA

Desde el punto de vista geológico, la provincia de Almería presenta gran variedad y complejidad (Fig. 7). Encontramos cuatro grandes conjuntos de unidades geológicas, litológicas y estructurales. En su mayor parte la provincia está ocupada por la Zonas Internas y Externas de las Cordilleras Béticas. Las primeras, cuyos materiales pertenecen a la edad Paleozoica y Triásica y las segundas, por materiales del Trías Medio, Jurásico, Cretácico y Eoceno. Además, están presentes los materiales de las grandes Cuencas

Neógenas (Mioceno inferior y medio, Mioceno superior y Plioceno) y las rocas volcánicas del Mioceno medio y superior.

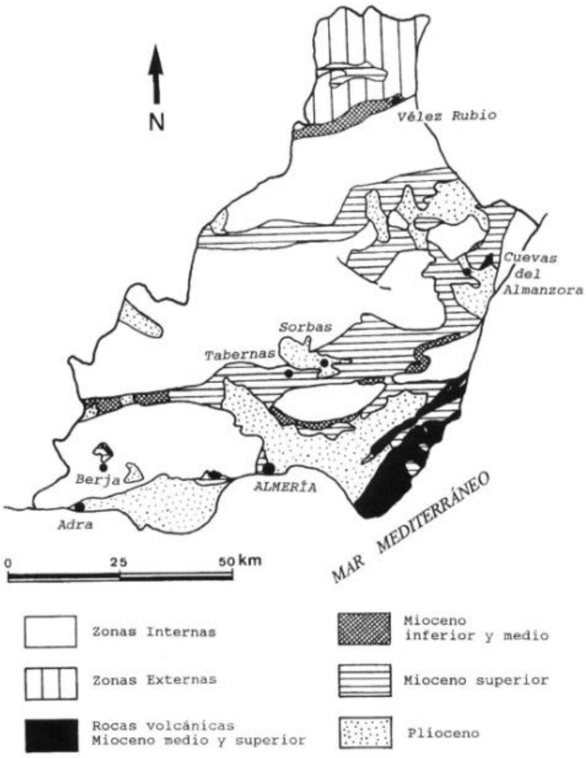


***Figura 7.*** *Esquema geológico de la provincia de Almería (Martín Penela et al., 1997)*

### 2.1.3.3. RELIEVE

La variabilidad altitudinal de la provincia va desde 2.609 m (Chullo) hasta el nivel del mar. Este brusco contraste topográfico en tan poco espacio, delimita tres grandes sectores: sierras, depresiones neógenas y zonas costeras. Estas diferencias altitudinales hacen que sólo el 12% de la superficie presente un relieve llano o casi llano, el 65,5% muestra unas pendientes entre (6-13%) y el 22,5% de la superficie restante superan una pendiente del 13% (Fig. 8).

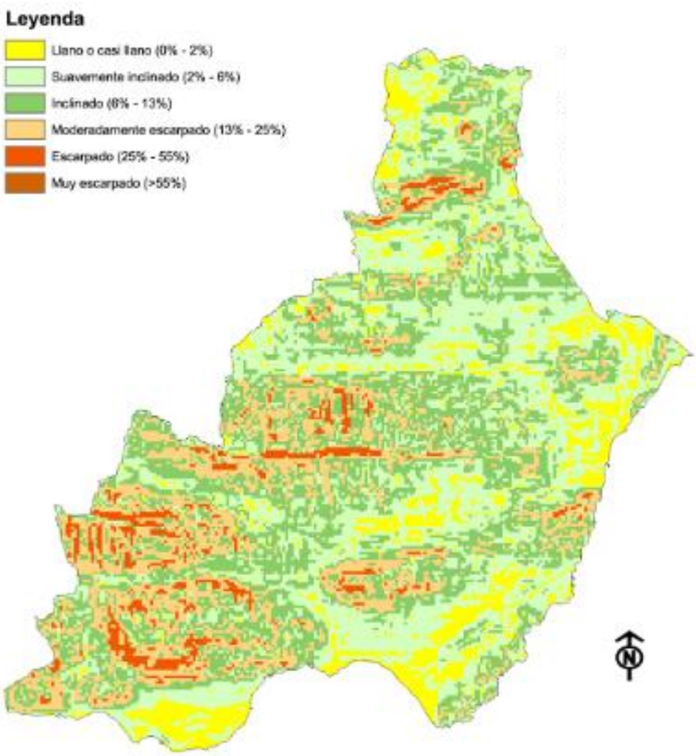


***Figura 8.*** *Distribución de pendientes de la provincia de Almería (Simón et al., 2005)*

### 2.1.3.4. VEGETACIÓN

En la vegetación tan característica de la provincial, podemos diferenciar cuatro pisos bio-climáticos (Fig. 9). El piso Termomediterráneo se caracteriza por casi la ausencia de bosques, predominando los arbustos espinosos y el matorral subdesértico. Es el dominante en nuestro área de studio.

Respecto a las series de vegetación (Fig. 10), en la zona donde se sitúan los suelos estudiados destacan las series semiárida del lentisco, la del azufaifo, la del arto y la vegetación tabernense sobre margas subsalinas.

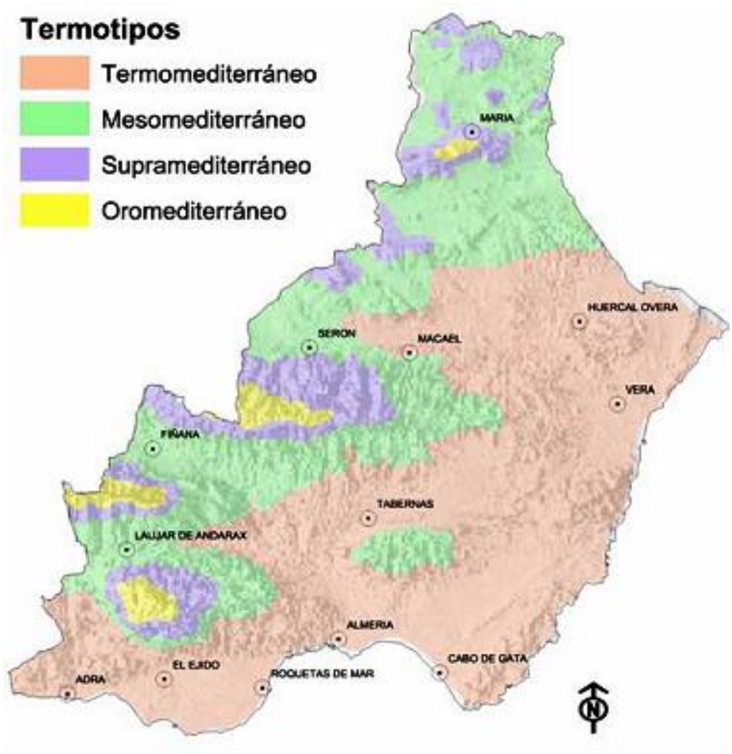


***Figura 9.*** *Termotipos de la provincia de Almería (Simón et al., 2005)*


***Figura 10.*** *Series de vegetación de la provincia de Almería (Simón et al., 2005)*

### 2.1.3.5. ACCIÓN ANTRÓPICA

El consumo de madera, la minería y la extensión de campos de cultivo (sobretodo bajo plásticos e intensivos) son los tres factores que más han transformado el suelo en la provincia de Almería. En la figura 11 se muestra las principales zonas cultivadas en la provincial, destacando la zona del Bajo Almanzora, el Campo de Níjar y el Campo de Dalías.

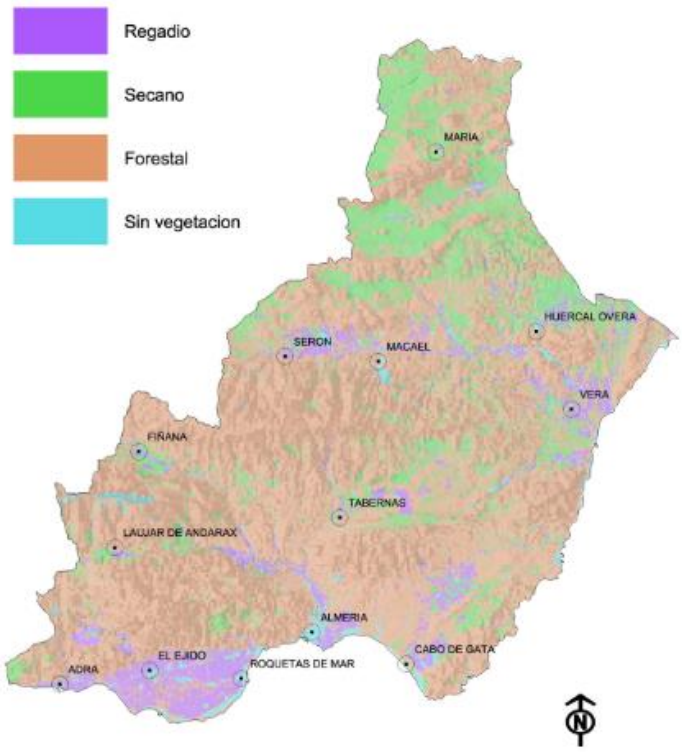


***Figura 11.*** *Principales zonas cultivadas en la provincia de Almería (Rubio et al., 2005)*

## 2.2. ANTECEDENTES

Los estudios previos y antecedentes edáficos de la zona se basan en mapas de suelos a gran escala o en estudios muy puntuales de zonas muy próximas a las fincas de estudio. Los mapas de suelos son el resultado de diversos estudios realizados a lo largo de los años, como por ejemplo, el de FAO (1967) en su publicación "*Mapa de Suelos Europeos*", donde destacan los Serosems y los suelos Pardos Rojizos asociados a los Litosoles. Una década más tarde, la Junta de Andalucía en su publicación "*Catálogo de los Suelos de Andalucía*", hizo referencia a los diferentes tipos de suelos de la Comunidad Autónoma. La Comisión de las Comunidades Europeas también editaría un "*Mapa de Suelos de Comunidades Europeas*" y, años más tarde, publicó "Memoria y Cartografía de Suelos". Todas estas publicaciones a gran escala y, por tanto, poco aplicables a una zona concreta.

Sumándose a la aportación de información de los suelos de la zona, el Ministerio de Agricultura, Pesca y Alimentación, en 1981, también editó "*Mapas de Cultivos y Aprovechamientos*". Análogamente, el Instituto Tecnológico Geominero de España publicó el "*Mapa Geológico*" de diferentes zonas de la provincial, a escala 1:50.000. En 1991, bajo el marco del Proyecto LUCDEME (lucha contra la desertificación en el Mediterráneo) se comenzaron a publicar "*Memorias y Mapas de Suelos*", a escala 1:100.000, de toda nuestra zona de studio.

La erosión ha sido un fenómeno muy estudiado, debido al cambio de orografía que produce el desplazamiento del material del suelo. En 1941, Ralph Bagnold publicó "*La física de la arena soplada y las dunas del desierto*". En ese studio, se analizaba la formación y el movimiento de las dunas de arena en el desierto de Libia. Con el paso de los años, esta línea de investigación se siguió desarrollando y aparecieron otras publicaciones como "*Soil and Water conservation for production and environmental protection*" (Troeh et al., 1980) o "*Erosion, Transportation and Sedimentation performed by the atmosfere*" (Udden, 1984). A mediados de los 90, se publicó "*Erosión y Conservación del suelo*" (Morgan, 1997). En este libro, Morgan resume con precisión el proceso de erosión y habla de cómo habría que enfocar la conservación del suelo, basándose principalmente en técnicas que reduzcan la erosión. Un año más tarde, en la Universidad de Almería, se edita “*Análisis de las direcciones de los vientos en Andalucía*” (Viedma, 1998). En trabajos más actuales, como los de Simón et al. (2005), se presenta un “*Mapa de Suelos de la provincia de Almería*”, a escala 1:100.000, y se analizan causas y efectos de la degradación de esos suelos.

Desde el punto de vista físico, el viento es un vector que posee intensidad (velocidad), dirección y sentido. Udden (1984) confirma que la velocidad del viento es menor cerca de la superficie del suelo y que aumenta con la altura. Según Morgan (1997), el factor principal de la erosión eólica es la velocidad del viento.

Con respecto a los vientos en la provincia de Almería, existe un registro muy elevado de número de días de viento al año. El régimen de vientos es de carácter estacional, siendo la dirección N la que predomina desde noviembre a febrero, con su máxima en el mes de diciembre, y las direcciones E y SW las predominantes en los meses de junio, julio y agosto, con un máximo en el mes de julio (Simón et al., 2005). En la figura 12, podemos observar la rosa de los vientos para la provincial de Almería.

Almería, diciembre Almería, julio

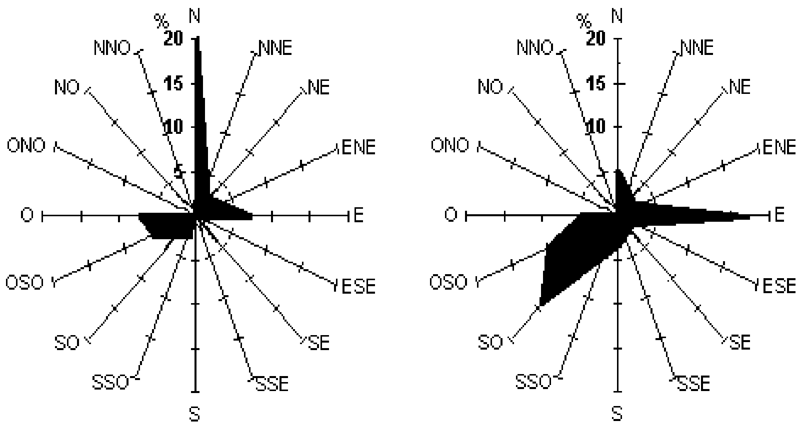


***Figura 12.*** *Frecuencia de las direcciones del viento en diciembre (izquierda) y julio (derecha) en la Provincia de Almería (Simón et al., 2005)*

Respecto a la degradación del suelo por la erosión eólica, FAO (1980) definió la degradación de suelo, globalmente, como *"el conjunto de procesos que rebajan la capacidad actual y potencial de suelo para producir cualitativa o cuantitativamente, bienes y servicios"*. La pérdida de suelo fértil hace que la tierra disminuya su vocación agrícola y su uso por el hombre, desapareciendo una importante fuente de riqueza. En nuestra zona, la degradación del suelo se debe en gran medida a la erosión eólica. Quirantes (1989) la definió como *"el proceso natural mediante el cual, el viento arranca y transporta partículas del suelo, desgastándolas, arrastrándolas y haciéndolas incidir sobre materiales y áreas"*. Estudios previos estiman que alrededor de 42 millones de hectáreas sufren erosión eólica en el mundo. El problema sucede en la mayoría de los países europeos, pero es la región mediterránea la más castigada.

Podemos considerar que los efectos producidos por la erosión eólica son de tres tipos:

- Superficiales: Estos afectan sobre todo a los cultivos, siendo la fase de plántula la más vulnerable, ya sea por el daño que produce la arena transportada o por la pérdida de tierra donde se asienta, teniendo como consecuencia el sistema radicular al descubierto.

- Edáficos: En este caso las acciones alteran, destruyen o transforman las texturas de los suelos. El viento arranca y transporta fracciones finas, dejando in situ las fracciones mayores del suelo. Esto provoca que el suelo se torne más arenoso, implicando más sensibilidad a la erosión, además de producir una pérdida en la productividad del mismo y menos capacidad de retención de agua.

- Secundarios: Estos se suman a los anteriores, por ejemplo, el transporte de materiales salinos hacia zonas de cultivo contribuyendo asimismo a salinizar los suelos.

Todos estos efectos conducen a una degradación progresiva de los recursos edáficos

(Quirantes, 1987). Para reducir problemas de degradación es necesario conocer el proceso de erosión eólica, cuantificarlo y conocer los principales factores que lo controlan.

La erosividad del viento es lineal y fuertemente dependiente de su velocidad (Lyles et al., 1983). Sin embargo, la erosionabilidad eólica del suelo está controlada por diversas propiedades del mismo y de la vegetación, como el tipo de suelo (Merrill et al., 1999), el contenido de agua y materia orgánica (García-Moreno, 2006) o la rugosidad del suelo (Asensio et al., 2019).

# INTRODUCCIÓN

# 3. INTRODUCCIÓN

La erosión eólica del suelo causa problemas ambientales, sociales y económicos que tienen un impacto adverso en la salud humana, además de aumentar la contaminación, el daño a los cultivos y la deposición de arena en pozos y arroyos (Novara et al., 2011; Sharifikia, 2013). Algunas regiones se ven más afectadas que otras por la erosión eólica, esto se debe principalmente al clima local (Borrelli et al., 2016; Weber et al., 2017). Una combinación del clima y las condiciones de la superficie del suelo afectan a la erosión eólica y, por lo tanto, a la pérdida de productividad del suelo.

En áreas áridas y semiáridas, donde las precipitaciones son escasas y los vientos son a menudo fuertes, la erosión eólica reposiciona grandes cantidades de suelo (Burtiev et al., 2013), lo que puede causar serios problemas agrícolas y ambientales, como la contaminación (Yildiz et al., 2017), una disminución en el estado hídrico del suelo (Kravchenko et al., 2016) y cambios de textura, o puede enterrar las plantas antes o después de la emergencia. Por lo tanto, se necesitan más estudios para ayudar en las políticas y toma de decisiones (Panagos et al., 2012).

La humedad del suelo es un factor muy importante para disminuir la erosionabilidad eólica del mismo, ya que eleva el umbral de velocidad del viento al aumentar la cohesión del suelo (Sharratt et al., 2013). La alta variabilidad temporal y espacial en el umbral de la velocidad del viento tiene un impacto significativo en la predicción de qué partículas serán transportadas por el viento (de Oro y Buschiazzo, 2009).

Lozano et al. (2013) y Giménez et al. (2019) analizaron las relaciones entre la velocidad del viento, la erosión que provoca, la influencia del tipo de suelo y de la vegetación en regiones semiáridas. La erosión eólica influye en el secado del suelo y la pérdida de nutrientes (Molchanov et al., 2015), ambos condicionados por la compactación de la superficie del suelo. La vegetación protege el suelo de la erosión eólica al reducir la velocidad del viento, con lo que reduce la erosionabilidad del suelo y atrapa el material erosionado (Touré et al., 2011; Leenders et al., 2011; Asensio et al., 2015b). La cubierta vegetal actúa como un cortavientos, obligando a que el aire fluya a través de ella de manera más lenta y rápida por la parte superior (Molina-Aiz et al., 2006). La intensidad de la erosión eólica puede cambiar las propiedades inherentes de los suelos y la cubierta vegetal (Li et al., 2004; López et al., 2017).

Analizando los sistemas de cultivo mediterráneos, Benlhabib et al. (2014) recomendaron tecnologías de cultivo sostenibles, que mostraron un efecto significativamente positivo en la productividad y el rendimiento. Colazo y Buschiazzo (2010, 2015) y Zobeck et al. (2013) confirmaron que el cultivo aumentó la fracción erosionable (FE) del suelo, por el viento, y redujo la estabilidad de los agregados secos en suelos de textura media, lo que debilitó la estructura del suelo además de provocar la pérdida de MO y la descomposición de los agregados. Fryrear et al. (1994) propusieron el uso de una ecuación de regresión múltiple para calcular la FE, cuando no se dispone de un tamiz rotatorio.

En ausencia de labranza, hay más vegetación natural y agregación del suelo, lo que reduce la pérdida de suelo por el viento al disminuir su velocidad, aumentando aún más la capacidad de capturar el material perdido (Touré et al., 2011; Asensio et al., 2015). El clima y la variabilidad espacial y temporal en el umbral de la velocidad del viento influyen fuertemente en la predicción de la cantidad y el tipo de partículas arrastradas por el viento (De Oro y Buschiazzo, 2009; Borrelli et al., 2016). En áreas marginales, donde no se aplican estrategias conservacionistas, el sobrepastoreo, el abandono de las tierras de labranza, la deforestación, etc., intensifican la erosión eólica y generan considerables pérdidas de suelo (Weber et al., 2017).

El movimiento de partículas sopladas, se ha simulado en túneles de viento durante muchos años. Estos sistemas de simulación han sufrido cambios a lo largo del tiempo. Hay muchos modelos derivados de los datos obtenidos con los túneles de viento, pero pocos de esos túneles son adecuados para su uso en el campo. El prototipo patentado por la Universidad de Almería, no solo es aplicable a estudios agrícolas, sino que también añade algunos componentes específicos para los estudios de campo de la erosión eólica del suelo, como un láser-escáner (Giménez et al., 2019).

Igualmente, se han desarrollado muchos muestreadores, colectores o trampas de polvo para medir el material transportado por el viento (Goossens et al., 2000), aunque el Big Spring Number Eight (BSNE; Fryrear, 1986) y el Modified Wilson and Cook (MWAC; Wilson y Cook, 1980) son los muestreadores más utilizados, según Zobeck et al. (2003). La elección del recolector depende del tipo de estudio a realizar, la precisión requerida y los recursos económicos disponibles. Los modelos disponibles varían según el tamaño, la forma, la eficiencia de recolección y el tipo de material a analizar. En un estudio de túnel de viento, Feras et al. (2008) demostraron que la eficiencia de las trampas de sedimentos depende principalmente del tamaño de las partículas y la velocidad del viento. La eficiencia del atrapamiento del recolector depende del tamaño de las partículas, porque las que se mueven por saltación se capturan más fácilmente que las que están en suspensión (Shao et al., 1993). Estudios previos han demostrado que la eficiencia de colectores BSNE y MWAC varía según el tamaño de partícula y la velocidad del viento (Méndez et al., 2011). Goossens y Buck (2012) encontraron que la eficiencia de los BSNE disminuyó con el diámetro de partícula, al igual que la eficiencia de MWAC (Feras et al., 2008). En una comparación entre la eficiencia de MWAC y BSNE en el campo, Mendez et al. (2011) observaron que la eficiencia aumentaba a medida que disminuía el tamaño de las partículas y aumentaba la velocidad del viento. Sin embargo, los estudios se realizaron con partículas de más de 10 µm, en un ambiente donde la sedimentación seca era el principal mecanismo de deposición.

El flujo vertical de sedimentos se puede medir mediante trampas colocadas a diferentes alturas (Basaran et al., 2011). La deposición juega un papel importante en el ciclo de nutrientes de los ecosistemas naturales, como se observa en el Sahel (Bielders et al., 2002), donde los sedimentos arrastrados por el viento se monitorearon utilizando trampas BSNE en un área arada manejada con un Sistema convencional.

En esta Tesis Doctoral utilizamos un collector de diseño propio, llamado Trampa Multidireccional (MDt), patentado por la Universidad de Almería, que incorpora varias ventajas y mejoras. Se fabrica de manera fácil y económica y no solo captura el material transportado por el viento desde la superficie del suelo, sino que lo diferencia por su dirección de origen. Mediante el uso de un grupo de mástiles con estos nuevos colectores a diferentes alturas, se puede determinar la pérdida o depósito total de partículas en el área de estudio, así como su composición en función del origen.

Por tanto, las partículas de origen conocido capturadas por el MDt pueden analizarse mediante difracción de rayos X, lo que permite una identificación y cuantificación rápidas y fiables de las fases cristalinas presentes en una muestra. Esto proporciona un valor añadido, ya que el tipo y la cantidad de mineral erosionado por el viento influyen fuertemente en la capacidad de intercambio catiónico del suelo y, por lo tanto, en la fertilidad del mismo.

# MATERIALES Y MÉTODOS

# 4. MATERIALES Y MÉTODOS

Se tomaron muestras de los 5 cm superficiales de suelos y se analizaron cuatro réplicas de cada tipología de suelo. Los datos de textura se encontraron mediante el método de la pipeta de Robinson. El contenido de carbono orgánico se analizó utilizando el método de digestión húmeda Walkley-Black. Se utilizó volumetría de gas para determinar el contenido de carbonato. Para determinar la densidad aparente, se usaron cilindros de 100 $cm^3$ de modo que, el peso seco de la muestra pudiera referirse al volumen del cilindro.

La fracción erosionable de los suelos, por el viento, se calculó siguiendo la Ec. (1) de Fryrear et al. (1994):

$$FE = 29.09 + 0.31\ \text{arena} + 0.17\ \text{limo} + 0.33\ \text{arena}/\text{arcilla} - 2{,}59\ \text{materia orgánica} - 0{,}95\ CaCO3 \quad (1)$$

donde todas las variables, incluida la fracción erosionable, se expresan en %.

La erosión eólica se monitorizó en un túnel de viento con estructura telescópica (Fig. 13). La sección central está equipada con un escáner láser 3D NextEngine Desktop para registrar los cambios en el microrrelieve y, conocida la densidad del suelo, poder calcular el volumen del suelo erosionado (Asensio et al., 2016 y 2019). Las figuras 14 y 15 hacen referencia a los components del túnel de viento patentado.

***Figura 13.*** *Estructura telescópica de nuestro túnel de viento e imagen del mismo desplegado*

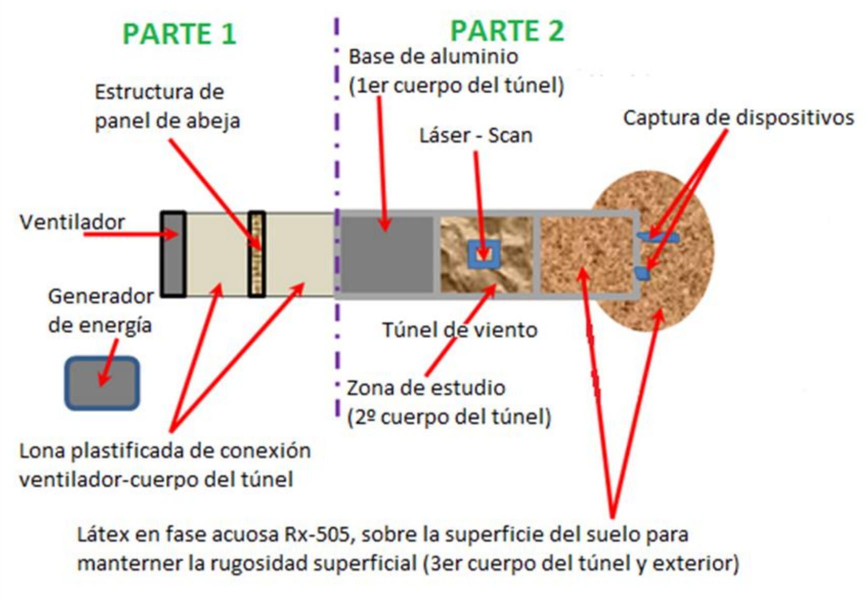


***Figura 14.*** *Esquema de la disposición de componentes del túnel de viento*

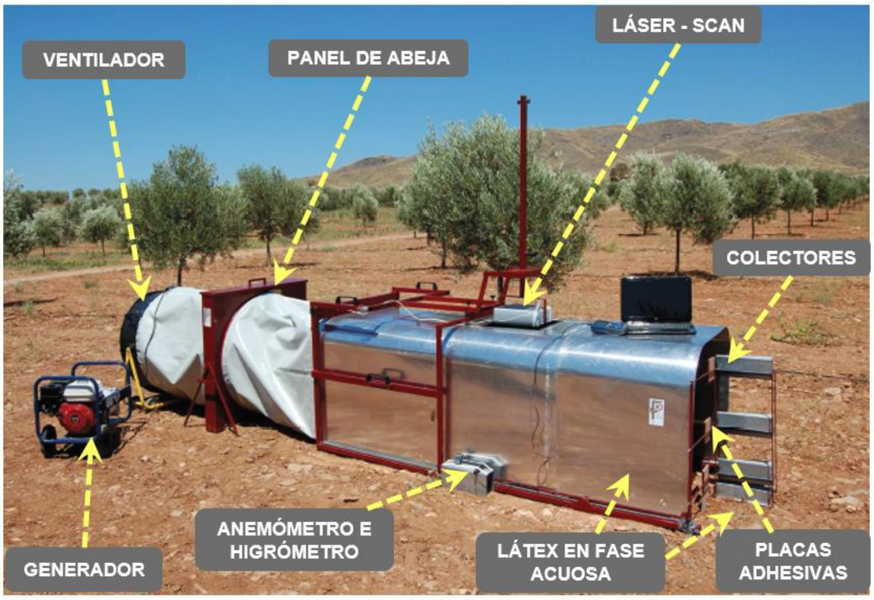


***Figura 15.*** *Principales componentes del túnel de viento*

De acuerdo con los criterios de Fister y Ries (2009), los experimentos del túnel de viento duraron diez minutos a una velocidad del viento de 7.6 $m \cdot s^{-1}$ monitoreada a una altura de 70 cm. Este valor de velocidad del viento es el promedio diario máximo registrado en los últimos 20 años por las estaciones agroclimáticas de nuestra zona. El terreno se escaneó antes y después de la simulación de viento, en cada caso. Estos escaneos proporcionaron dos nubes de puntos para cada parcela, tanto en suelos encostrados como en los mismos recien labrados (Fig. 16), a partir de las cuales se generaron dos modelos digitales de terreno (DTM). El volumen de suelo erosionado se estimó como la diferencia entre los DTM (Fig. 17), a través de la realización de mapas de erosion eólica (fig. 18). Finalmente, el volumen de suelo perdido puede estimarse, conociendo su densidad aparente (Asensio et al., 2016).

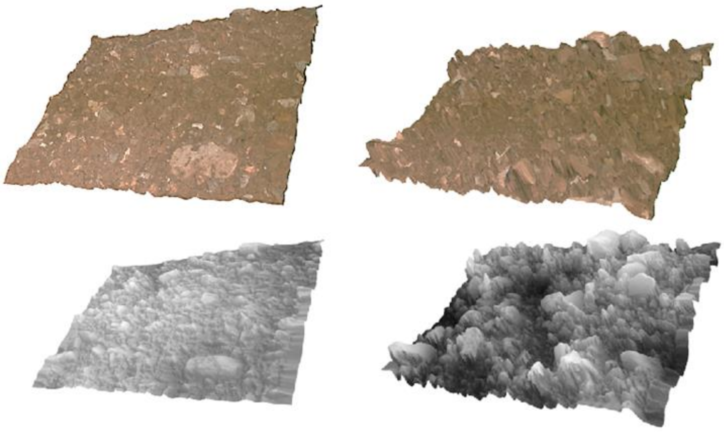

***Figura 16.*** *Ejemplos de vision real y MDTs de un Luvisol encostrado y recien labrado, del Norte de la zona de estudio*

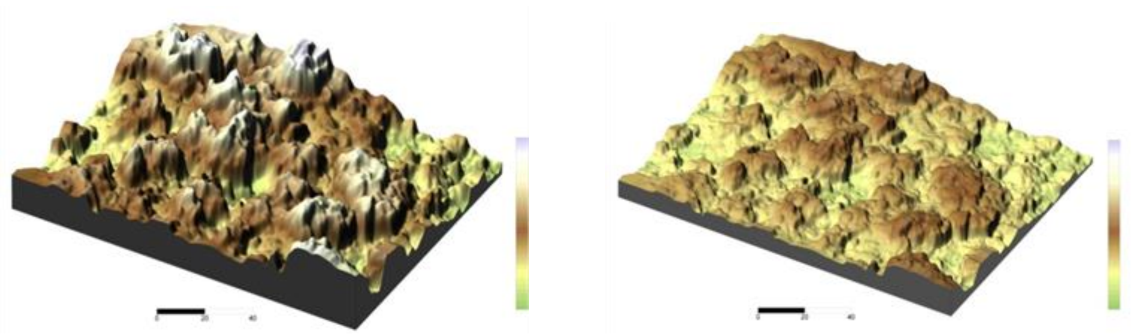

***Figura 17.*** *Ejemplo de MDTs de un Cambisol antes y después del soplado, del Norte de la zona de studio, para establecer diferencias*

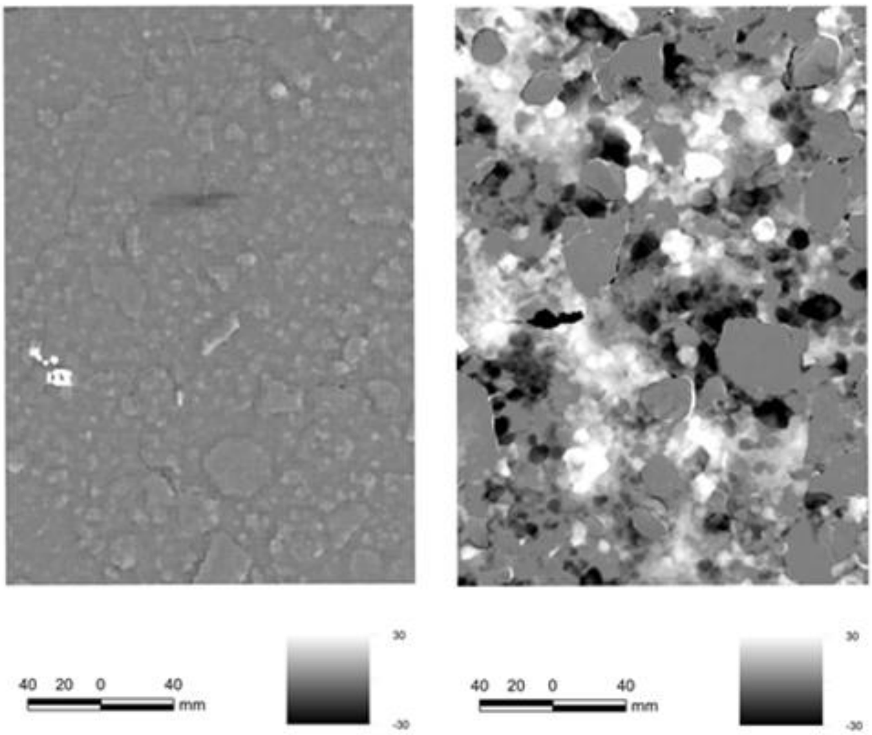


***Figura 18.*** *Ejemplos de mapas de erosión de un Luvisol encostrado y recien labrado, del Norte de la zona de estudio*

Este dispositivo experimental es adecuado para estudiar los efectos de una corriente de viento de velocidad constante en la superficie del suelo. Esta configuración es especialmente favorable para generar comparaciones entre parcelas y sitios, ya que la velocidad de la corriente de aire es un parámetro fijo reproducible de manera confiable. Elegimos cuatro parcelas diferentes para cada tipo de suelo, de modo que los datos recopilados reflejaran la variabilidad natural de las parcelas estudiadas.

Por otra parte, también utilizamos en nuestro estudio colectores BSNE (Fryrear, 1986), hechos de metal galvanizado. Estos colectores constan de dos partes, una bandeja inferior donde se recoge la muestra y otra que se fija encima de ella, pero con la parte superior e inferior de malla de 0,3 y 1 mm de diámetro, respectivamente, ambas de forma trapezoidal (Fig. 19). El material entra a través de una abertura rectangular de 2 cm de ancho por 5 cm de alto, debajo de la malla superior. Cuando la corriente de aire que transporta el material ingresa en el colector, la velocidad del viento se reduce por la forma trapezoidal del colector, y al chocar con la superficie opuesta, el polvo cae por la malla inferior a la bandeja colectora, mientras que el aire escapa por la malla superior. La malla inferior de 1 mm ralentiza el movimiento del material depositado, por lo que no se pierde el polvo más fino ni se produce una disgregación adicional del material recogido. Cada colector se colocó en un mástil, a diferentes Alturas, con una veleta adjunta.

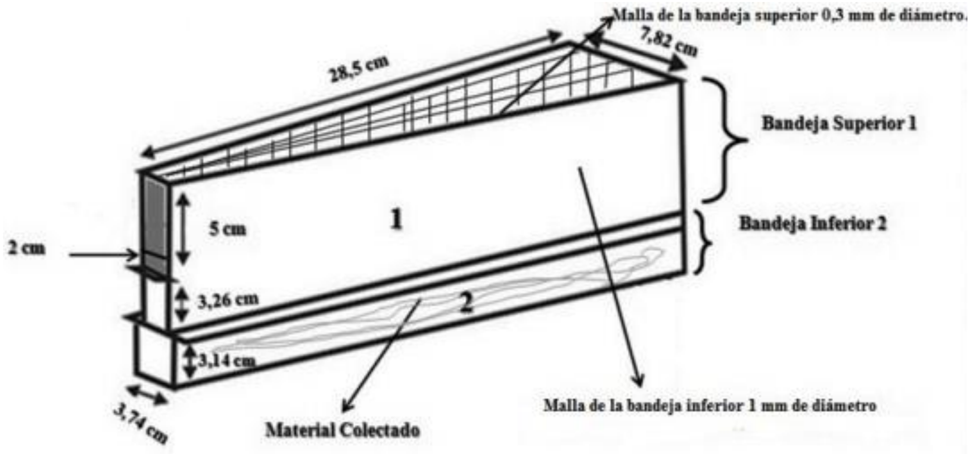


***Figura 19.*** *Imagen esquemática de un collector BSNE*

Junto con los colectores BSNE, también utilizamos nuestros propios colectores, patentados por la Universidad de Almería (Asensio et al., 2015a) y fabricados con una impresora industrial 3D, a partir de un filamento termoplástico de politereftalato de etileno modificado con glicol (PETg). El PETg es un material fuerte, ideal para objetos sometidos a esfuerzos mecánicos; es duro, flexible y resistente. El aire que transporta el material entra en el colector a través de una abertura rectangular de 2 × 5 cm y una agalla en el interior modifica su movimiento. El material se deposita en una estructura desmontable en forma de toroidal en la base.

La principal innovación de este nuevo colector es la separación de las partículas sólidas recolectadas en función de la dirección del viento. El colector dispone de diversos recipientes en los cuales se depositan las partículas recolectadas diferenciadas según las diferentes direcciones del viento.

Como resultado del proceso de diseño, las figuras 20 a 24 muestran una vista en perspectiva del colector multidireccional, una vista en alzado, un corte del toroide del collector, una vista en sección según el plano de simetría del colector y el conjunto desplegado.

El colector multidireccional consta de una cámara de separación (1) en la que las partículas sólidas se separan del aire. Dicha cámara posee una abertura de entrada (2), una abertura de salida (3) y una abertura de descarga (4). La abertura de entrada (2) se encuentra preferiblemente contenida en un plano vertical. La abertura de salida (3) está situada en el lado opuesto a la abertura de entrada (2). La abertura de descarga (4) se encuentra en la base de la cámara de separación (1) y contenida en un plano horizontal. Hay una aleta (6) unida solidariamente a la cámara de separación (1), contenida en un plano vertical, que corta a la abertura de entrada (2) y a la abertura de salida (3), quedando situada la abertura de salida (3) entre la abertura de entrada (2) y la aleta (6). Al mástil vertical (7) se encuentra articulada la cámara de separación (1), de forma que el conjunto formado por esta cámara (1) y la aleta (6) puede girar libremente respecto a su eje. Este mástil vertical (7) dispone de un contenedor (12) en forma de toroide, que contiene ocho recipientes (13) que dividen en su totalidad dicho contenedor (12) en porciones angulares, de forma que las partículas que pasan a través de la abertura de descarga (4) se depositan en el fondo de los recipientes (13). La posición que tenga en cada momento el orificio de descarga (4) determina el recipiente (13) en el cual se depositan las partículas separadas en la cámara (1). También dispone este dispositivo de una tapa (14) que cubre a los recipientes (13) por su parte superior y que es atravesada por la abertura de descarga (4). Esta tapa (14) está fijada a la cámara (1) y gira solidariamente con ella respecto al eje del mástil (7).

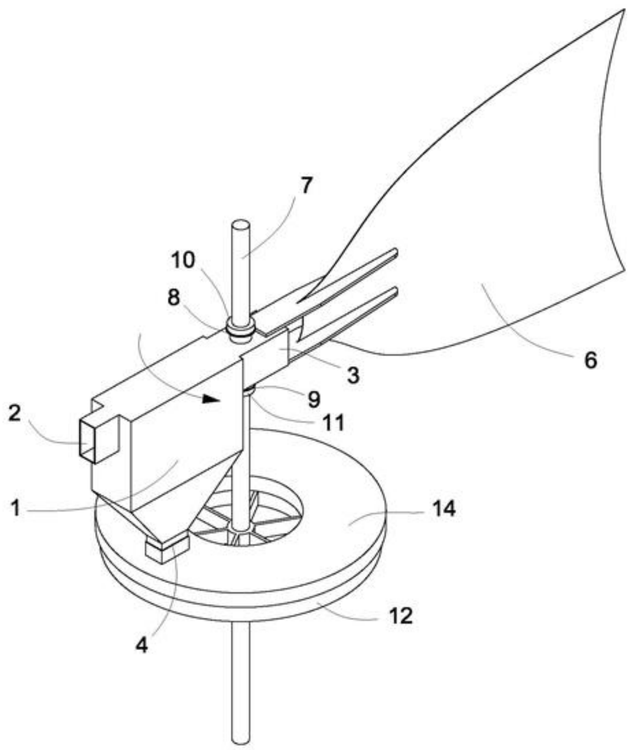


***Figura 20.*** *Vista en perspectiva del colector multidireccional*

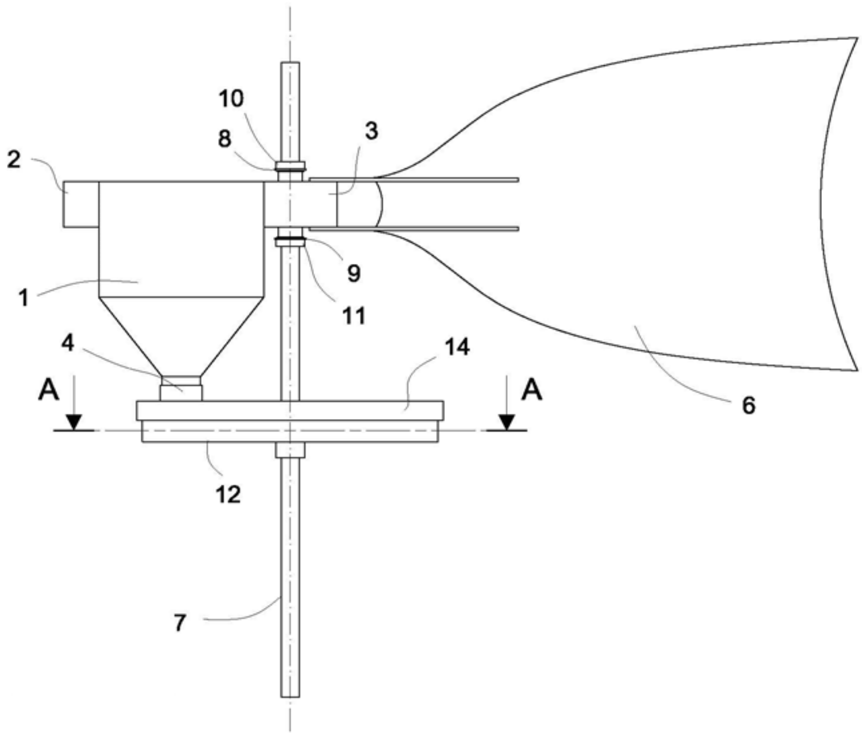


***Figura 21.*** *Vista en alzado del colector*

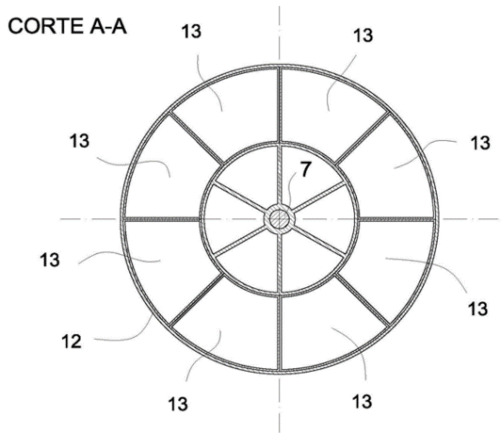


***Figura. 22.*** *Corte de la Figura 21, tomado a lo largo de la línea A-A*

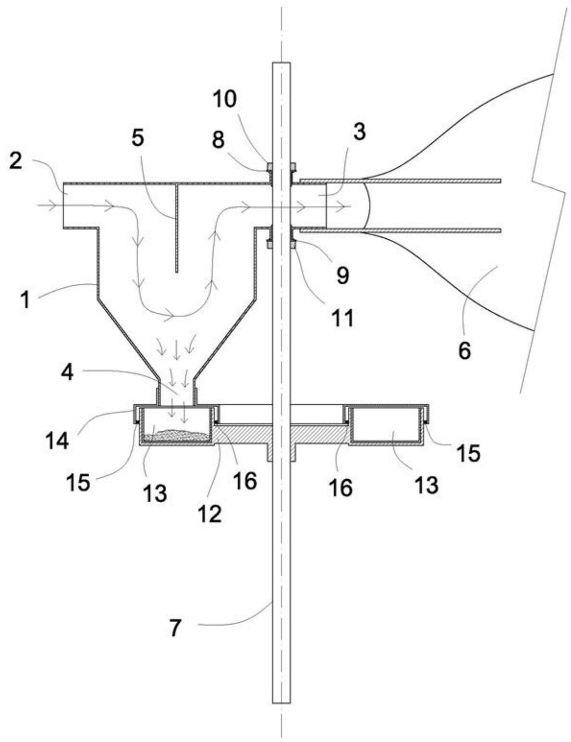


***Figura 23.*** *Vista en sección según el plano de simetría del colector*

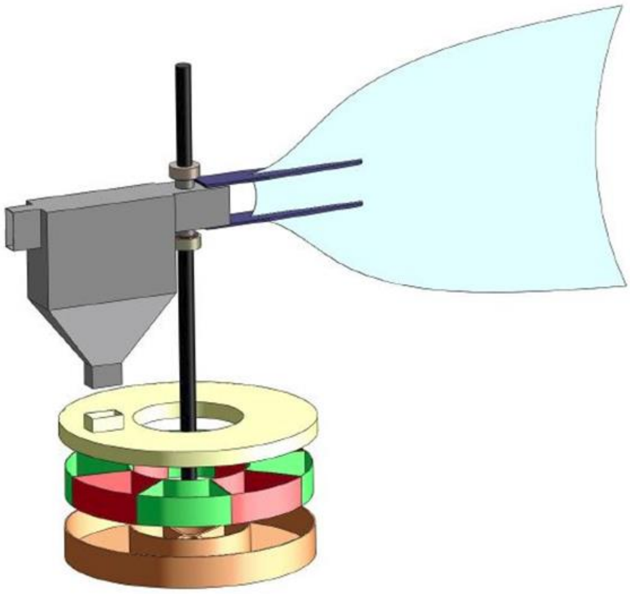

***Figura 24.*** *Vista del colector desplegado*

Se montó una red de nueve mástiles de veleta con trampas BSNE y MDt a 0.35, 0.70, 1.05 y 1.40 m de altura, de manera que sus entradas se enfrentaran a la dirección principal del viento en cada momento. La eficiencia del colector BSNE (η), que Fryrear et al. (1994) y Goossens et al. (2018) estimaron en 65%, fue particularmente buena para recolectar el material muy fino. Según Asensio et al. (2015a), la eficiencia del colector MDt (74%) es más alta para tamaños de grano fino. Los mástiles giratorios se separaron 50 m para evitar interferencias. Esto se realizó en cada tipo de suelo; la figura 25 muestra la distribución de los mástiles en un Anthrosol del Este de nuestra zona. Ya sea para trampas BSNE y MDt, el período de medición fue de 24 h y posteriormente, se recogió y analizó el polvo acumulado.

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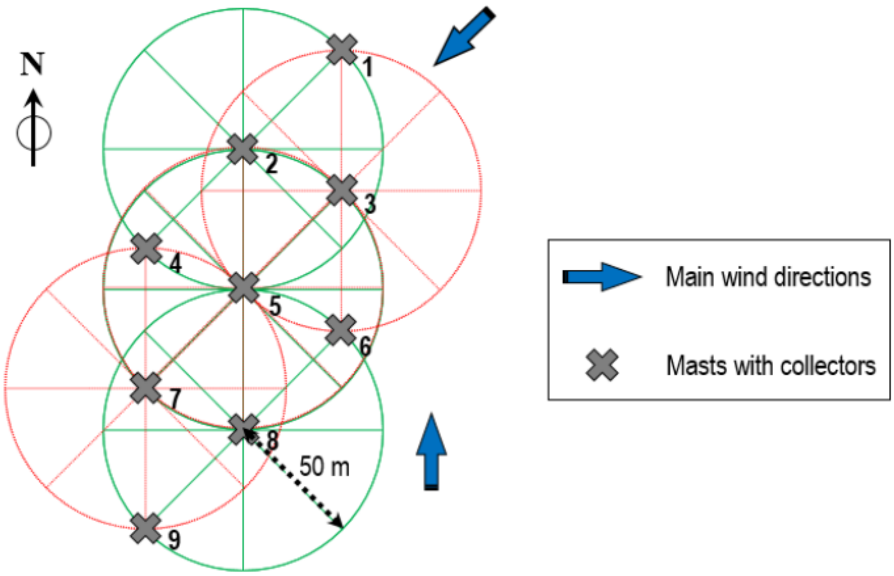


***Figura 25.*** *Distribución de mástiles y direcciones predominantes del viento en el Anthrosol del Este de la zona de estudio*

Tanto los colectores BSNE, como los MDt, se colocaron a diferentes alturas en el mástil a partir de 0.35 m (Fig. 26), por lo que la diferencia en la tasa de pérdida de suelo con la distancia al suelo se tubo que medir experimentalmente. Esto se logró mediante un modelo matemático que predice la cantidad de sedimento modelado en la superficie del suelo (Basaran et al., 2011). La cantidad de material depositado o perdido se calculó como la diferencia en la tasa de transporte de sedimentos entre los datos de los mástiles ubicados a barlovento y sotavento, en la dirección principal del viento. De esta forma, las diferencias negativas indicaron pérdidas y las positivas ganancias de material.

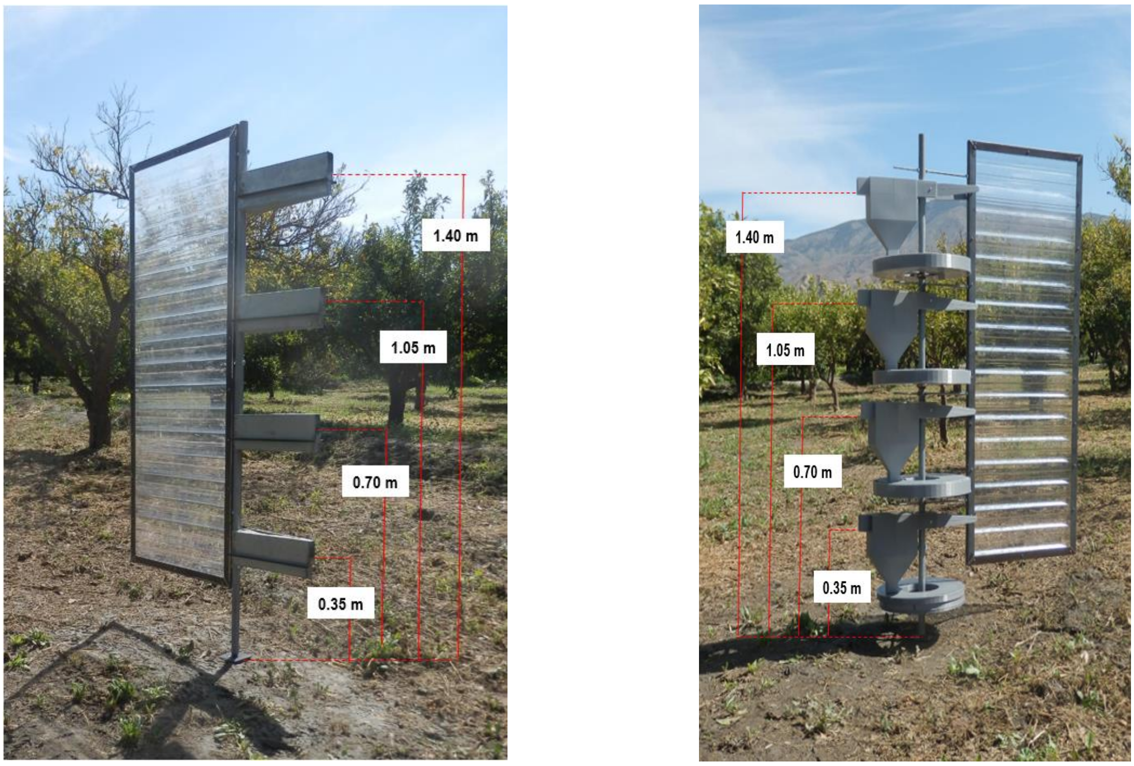


***Figura 26.*** *Disposición de los colectores BSNE y MDt en los mástiles en un Fluvisol del Oeste de la zona de estudio*

Aunque la difracción de rayos X (XRD) es una técnica semicuantitativa que puede producir errores absolutos, con condiciones experimentales e interpretación estandarizadas, las variaciones relativas son reproducibles. Para las muestras de polvo, utilizamos el difractómetro de la figura 27 de los Servicios Técnicos de la Universidad de Almería, modelo "Davinci D8 Advance" (Bruker Corporation, Madison, WI, EE. UU.), con tubo de radiación de cobre (CuKα, $\lambda = 1.54$ Å). Los resultados (Fig. 28) se analizaron con el programa XPrep y se evaluaron los datos con el programa EVA, ambos en el paquete de software Diffract Evaluation 2.1.


***Figura 27.*** *Equipo de Difracción de Rayos X de polvo "D8 ADVANCE modelo DAVINCI"*

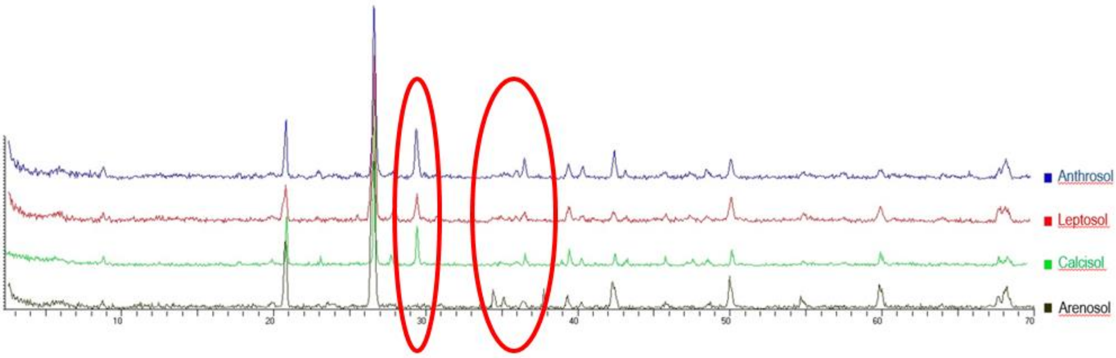


***Figura 28.*** *Ejemplos de difractogramas de polvo de algunos de los suelos estudiados*

# PUBLICACIONES CIENTÍFICAS

# 5. PUBLICACIONES CIENTÍFICAS

- ARTÍCULO 1: *SOIL WIND EROSION CHARACTERIZATION IN SOUTH-EASTERN SPAIN USING TRADITIONAL METHODS IN FRONT OF AN INNOVATIVE TYPE OF DUST COLLECTOR.*

- ARTÍCULO 2: *MULTIDIRECTIONAL TRAPS AS A NEW ASSESSMENT SYSTEM OF SOIL WIND EROSION.*

- ARTÍCULO 3: *IMPACT OF WIND DIRECTION ON ERODIBILITY OF A HORTIC ANTHROSOL IN SOUTHEASTERN SPAIN.*

## 5.1. ARTÍCULO 1:

Guerrero, R.; Valenzuela, J.L.; Torres, J.L.; Lozano, F.J.; Asensio, C. 2020. *Soil wind erosion characterization in south-eastern Spain using traditional methods in front of an innovative type of dust collector. INTERNATIONAL AGROPHYSICS, 34(4): 503-510* (doi.org/10.31545/intagr/131099).

RESUMEN:

El movimiento de las partículas del suelo por el viento se puede medir utilizando túneles y colectores de viento o trampas de polvo. Probamos ambos en el sureste de España para comparar el movimiento en cuatro tipos de suelo. Nuestras pruebas se llevaron a cabo en un Anthrosol intensamente labrado, un Leptosol y un Arenosol sin arar, y finalmente en un Cambisol con un cultivo de olivos. Estimamos la pérdida de suelo utilizando un túnel de viento con un escáner láser incorporado, y luego comparamos los resultados con los registros de nueve mástiles, con cuatro colectores BSNE a diferentes alturas, y lo mismo para otros nueve mástiles, pero con un nuevo tipo de trampa de polvo que denominamos Multidireccional. Los colectores pueden diferenciar entre la pérdida total y la deposición de partículas, hecho que no se puede detector, a mayor escala, en el túnel. Los resultados de los colectores BSNE y nuestro túnel de viento mostraron un alto grado de correlación ($R^2$ = 0.933), encontrándose una correlación aún más estrecha con los colectores Multidireccionales, MDt ($R^2$ = 0.978). Además, los nuevos colectores son muy eficientes y fáciles de fabricar a partir de filamentos termoplásticos con una impresora industrial 3D.

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# Soil wind erosion characterization in south-eastern Spain using traditional methods in front of an innovative type of dust collector**

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A b s t r a c t. The movement of soil particles by the wind can be measured using wind tunnels and collectors, or dust traps. We tested both in Southeast Spain in order to compare movement in four types of soil. Our tests were carried out in a well-tilled orchard on an Anthrosol, an unploughed Leptosol and Arenosol, and finally on an olive-cropped Cambisol. We estimated soil loss using a wind tunnel with a built-in laser-scanner, and then compared the results with records from nine vaned masts, each with four big spring number eight collectors at different heights, and the same for another nine masts but with a new type of dust trap known as the multidirectional. The collectors can differentiate between overall loss and particle deposition, which is not detectable on a larger scale in the tunnel. The results from the big spring number eight traps and our wind tunnel showed a high degree of correlation ($R^2 = 0.933$) and an even closer correlation with the multidirectional trap ($R^2 = 0.978$). Moreover, the new multidirectional trap collectors are very efficient and easy to manufacture from thermoplastic filaments with an industrial 3D printer.

K e y w o r d s: dust collector, semi-arid environment, tilled soil, unploughed soil, wind tunnel

## INTRODUCTION

The wind erosion of soil causes environmental, social and economic problems which have an adverse impact on human health, as well as increasing pollution, crop damage and sand deposition in wells and streams (Novara *et al*. 2011; Sharifikia 2013). Some regions are more affected than others by wind erosion, this is mainly due to the local climate (Borrelli *et al*., 2016; Weber *et al*., 2017). A combination of the climate and soil surface conditions affect wind erosion, and thereby the loss of soil productivity. In arid and semiarid areas, where rainfall is scarce and winds are often strong (Burtiev *et al*., 2013), wind erosion repositions huge amounts of soil, which may cause serious agricultural and environmental problems, such as pollution (Yildiz *et al*., 2017), a decline in soil water status (Kravchenko *et al*., 2016) and textural changes, or bury plants before or after emergence. Soil moisture is a very important factor in decreasing soil erodibility, as it raises the threshold wind velocity by increasing soil cohesion (Sharratt *et al*., 2013). The high temporal and spatial variability in threshold wind velocity has a significant impact on predicting which particles will be transported by the wind (de Oro and Buschiazzo, 2009).

Lozano *et al*. (2013) and Giménez *et al*. (2019) analysed the relationships between wind speed, wind erosion, soil type and vegetation in semiarid regions. Wind erosion influences soil drying and nutrient loss (Molchanov *et al*, 2015), both of which are conditioned by soil surface compaction. Vegetation protects the soil from wind erosion by reducing wind speed, it also reduces soil erodibility, and traps eroded material (Touré *et al*., 2011; Leenders *et al*., 2011; Asensio *et al*., 2015b). Plant cover acts like a windbreak, forcing air to flow through it more slowly and faster

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over the top (Molina-Aiz *et al*., 2006). The intensity of wind erosion can change the inherent properties of soils and vegetation cover (Li *et al*., 2004; López *et al*., 2017).

The movement of blowing particles has been simulated in wind tunnels for many years. These simulation systems have undergone changes over time. There are many models derived from wind tunnel data, but few of them are suitable for use in the field. The prototype from the University of Almeria (Spain) has been patented and is not only applicable to agriculture, but also adds some components specific to soil wind erosion field studies (Giménez *et al*., 2019), such as a laser-scanner.

Many samplers, collectors or dust traps have also been developed for measuring the material carried by the wind (Goossens *et al*., 2000), although the Big Spring Number Eight (BSNE; Fryrear, 1986) and the Modified Wilson and Cook (MWAC; Wilson and Cook, 1980) samplers are the most commonly used, according to Zobeck *et al*. (2003). The choice of collector depends on the type of study to be carried out, the accuracy required and the financial resources available. The models available vary according to size, shape, collection efficiency and type of material to be quantified. In a wind tunnel study, Feras *et al*. (2008) demonstrated that sediment trap efficiency depends mainly on particle size and wind speed. Collector entrapment efficiency depends on particle size, because those moved by saltation are more easily captured than those in suspension (Shao *et al*., 1993). Previous studies have shown that the efficiency of BSNE and MWAC varies according to particle size and wind speed (Méndez *et al*., 2011). Goossens and Buck (2012) found that the BSNE efficiency decreased with particle diameter, as did MWAC efficiency (Feras *et al*., 2008). In a comparison between MWAC and BSNE efficiency in the field, Mendez *et al*. (2011) found that efficiency increased as particle size decreased and wind speed increased. However, studies were carried out with particles over 10 μm in an environment where dry sedimentation was the main deposition mechanism. Vertical sediment flow can be measured by traps placed at different heights (Basaran *et al*., 2011). Deposition plays an important role in the nutrient cycle of natural ecosystems, as observed in the Sahel (Bielders *et al*., 2002), where windblown sediment was monitored using BSNE traps in a conventionally managed ploughed area.

Our objectives were to study the material lost due to wind erosion in representative soil types in SE Spain, using different methods and to show the differences between the dust collected as reported by traditional studies and a new technique through an evaluation of the results.

## MATERIALS AND METHODS

The study area is located in Almería Province, Spain (Fig. 1). The climate is semi-arid Mediterranean with a mean annual temperature of 18.5°C and rainfall of 243 mm. The dominant geological material is a Miocene sedimentary series. The natural plant communities are isolated native shrubs, but at present, there is also intensive horticultural and tree crop activity. According to the IUSS Working Group WRB (2015), the soils studied are hortic Anthrosol (AT), eutric Leptosol (LP), endosalic Arenosol (AR) and calcaric Cambisol (CM).

Table 1 shows the locations, sampling date, average wind speed and direction, average temperature and relative air humidity at the studied sites. In all cases, there were wind gusts exceeding 14 m $s^1$.

Weather records were taken from the automatic meteorological station network of the Institute of Agrarian and Fishing Research and Education of Andalusia (IFAPA)

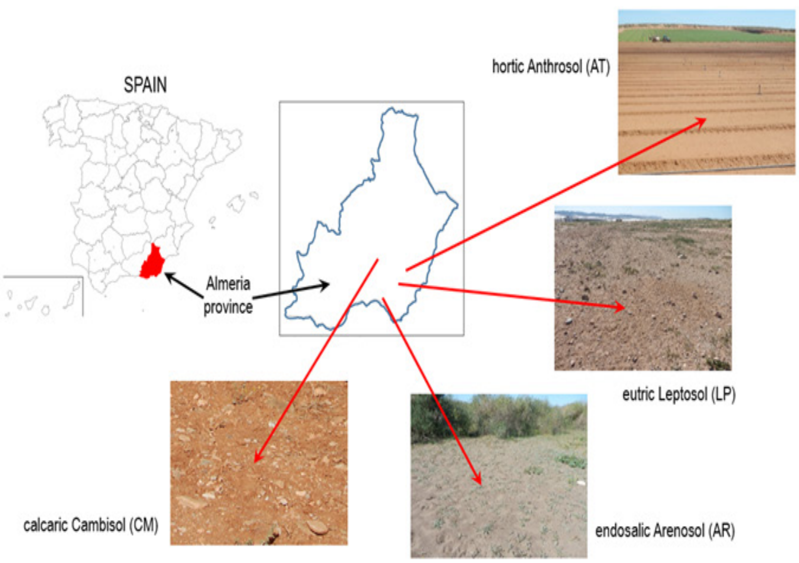


**Fig. 1.** Location of soils studied.

**Table 1.** Coordinates, altitude, sampling date and climatic characteristics of soils studied

| Sample | Location | | | Date 2019 | Averaged | | | |
|---|---|---|---|---|---|---|---|---|
| | Coordinates | | Altitude (m) a.s.l. | | Wind speed (m $s^{-1}$) | Direction (º) | Temperature (ºC) | Relative humidity (%) |
| AT | 36°58'57.94"N | 2°03'40.20"W | 205 | 29/05 | 2.9 | 67.0 | 20.8 | 51.0 |
| LP | 36°55'43.78"N | 2°11'19.68"W | 174 | 13/05 | 2.7 | 61.5 | 20.6 | 53.7 |
| AR | 36°50'32.10"N | 2°20'30.13"W | 8 | 26/03 | 2.9 | 87.7 | 17.6 | 38.4 |
| CM | 37°06'48.43"N | 2°18'19.67"W | 579 | 01/02 | 5.4 | 239.4 | 12.3 | 52.9 |

(http://www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/servlet/FrontController), an institution belonging to the Andalusian Regional Government.

Soils were sampled from the upper 5 cm of the land and four replicates of each sample were assayed. Textural data were found through the use of the Robinson pipette method. Organic carbon content was analysed using the Walkley-Black wet digestion method. Gas volumetry was used to determine the carbonate content. In order to determine bulk density, 100 $cm^3$ cylinders were used so that the sample dry weight could be referred to by cylinder volume.

Wind erosion was monitored in a wind tunnel with a telescopic structure (Fig. 2a). The centre section is equipped with a NextEngine Desktop 3D laser scanner to record changes in the microrelief and later, the volume of the eroded soil (Asensio *et al.*, 2016 and 2019). According to the criteria of Fister and Ries (2009), the wind tunnel

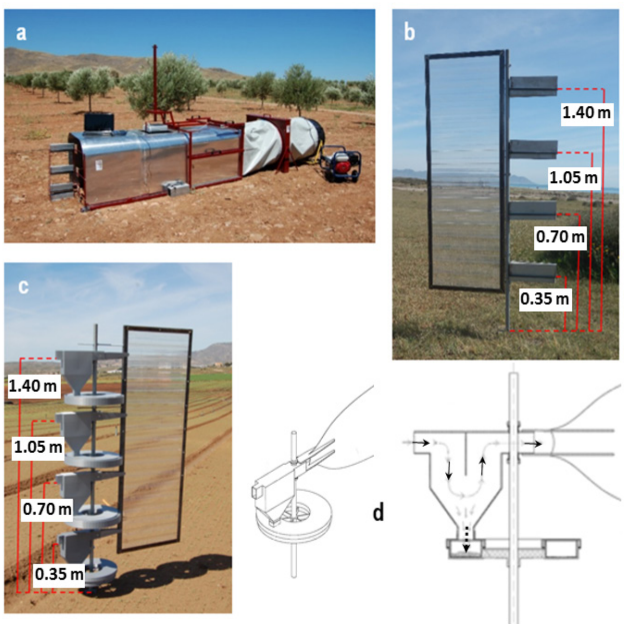


**Fig. 2.** Wind tunnel on Cambisols (a), mast and wind vane with BSNE collectors on Arenosols (b), mast and vane with MDt collectors on Anthrosols (c), schemes of MDt collectors (d).

experiments lasted for ten minutes at 7.2 m $s^{-1}$ wind speed monitored at a height of 70 cm. This wind speed value is the maximum daily average recorded over the last 20 years by agro-climatic stations in our area. The ground was scanned before and after the wind simulation, in each case. These scans provided two point clouds for each plot, from which two digital terrain models (DTMs) were generated. The eroded soil volume was estimated as the difference between DTMs. Thus, the estimate of soil volume lost could be used to estimate the amount of soil lost, by using the soil bulk density (Asensio *et al*., 2016). This experimental device is suitable for studying the effects of a steady-velocity-wind stream on soil surfaces. This setup is especially favourable for generating comparisons between plots and sites, since air stream speed is a reliably reproducible fixed parameter. Four different plots were chosen for every soil type, so that the data collected would reflect the natural variability of the test plots.

We also used BSNE collectors made from galvanized metal (Fryrear, 1986) in our study (Fig. 2b). These collectors have two parts, a lower tray where the sample is collected and another that is attached above it, but with the top and bottom made of 0.3 and 1mmdiameter mesh, respectively, both trapezoidal in shape. The material enters through a rectangular 2 cm wide by 5cm high aperture below the top mesh. When the stream of air carrying the material enters the collector, the wind speed is reduced by the collector's shape, and as it collides with the opposite surface, the dust falls through the bottom mesh to the collector tray, while the air escapes through the top mesh. The bottom 1mm mesh slows the movement of the material deposited, therefore the finest dust is not lost nor is there any additional disaggregation of the collected material. Each collector was placed on a mast with a wind vane attached to it.

Along with the BSNE collectors, we also used our own patented collectors (Asensio *et al*., 2015a) fabricated using an industrial 3D printer from a thermoplastic filament, ethylene polyterephthalate modified with glycol (PETg, Fig. 2c). PETg is a strong material, which is ideal for objects subjected to mechanical stress, it is hard, flexible and resistant. A diagram of this new collector design, which is referred to as a multidirectional trap (MDt), is shown in Fig. 2d. The air which carries the material enters the collector through a 2 × 5 cm rectangular opening and a grill inside modifies its movement. The material is deposited in a removable toroidal-shaped structure at the base. Future studies will allow the direction of origin of the captured materials to be determined through the use of north-facing compartments located in the MDt ring-shaped base. Each of these collectors is also attached to a mast with a weather vane (Fig. 2c). BSNE collector efficiency ($\eta$), which Fryrear *et al*. (1994) and Goossens *et al*. (2018) estimated to be 65%, was particularly good for collecting the very fine material. According to Asensio *et al*. (2015a), MDt collector efficiency (74%) is highest for fine grain sizes. Each collector experiment lasted for 24 h.

Nine wind vane masts with BSNE and MDt traps were mounted at 0.35, 070, 1.05 and 1.40 m heights, so that their inlets would face the main wind direction at each moment. The rotating masts were spaced 50 m apart to prevent interference (Fig. 3). Either for BSNE and MDt traps, the period of measurement was 24 h and later, the accumulated dust was collected and analysed.

As our collectors were placed at different heights on

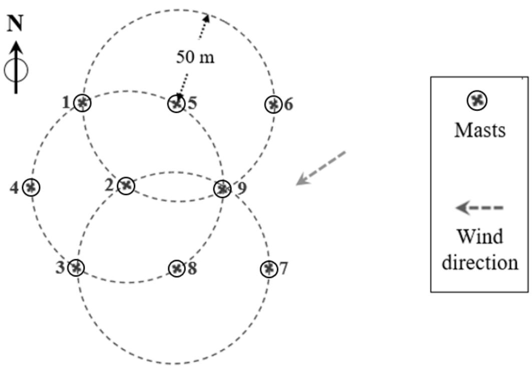


**Fig. 3.** Example of masts distribution on Leptosols.

the mast starting at 0.35 m, the difference in soil loss rate with distance from the ground could be experimentally measured. This was achieved by a mathematical model predicting the amount of sediment modelled at the surface of the soil surface. The sediment flux ($q_z$, kg m$^{-2}$) at each trap height ($z$, m) was obtained using Eq. (1):

$$q_z = \frac{m}{A}, \tag{1}$$

where: $m$ – sediment weight (kg) caught by each collector at a given height, $A$ – inlet area (m$^2$) of a collector.

Then, in Eq. (2), the sediment flux was predicted ($q_{z.exp}$, kg m$^{-2}$) by an exponential equation for every amount modelled:

$$q_{z.exp} = q_0 e^{-\alpha z}, \tag{2}$$

where: $q_0$ – amount of sediment modelled at $z = 0$ (kg m$^{-2}$), $\alpha$ – slope factor of the exponential regression equation (m).

Next, the sediment transport rate ($Q_r$, kg m$^{-1}$) was determined by integrating $q_{z.exp}$ (kg m$^{-1}$) predicted using Eq. (3):

$$Q_r = \int_0^h q_{z.exp}\, dz, \tag{3}$$

where: $h$ – maximum particle transportation height (m) recorded.

The total mass transport ($Q_t$, kg) was calculated by Eq. (4):

$$Q_t = \left(\frac{Q_r}{\eta}\right) L, \tag{4}$$

where: $\eta$ – trap efficiency, $L$ – plot width.

The amount of material lost (or deposited) was calculated as the difference in the sediment flux or sediment transport rate between the sampling points located windward and leeward of the prevailing wind direction. Thus, the positive differences indicated gains and the negative ones pointed to a loss of material.

The non-parametric Wilcoxon signed-rank test was performed to determine whether the amount of material captured at the same heights by BSNE and MDt collectors differed. The results of the comparison between the BSNE and MDt collectors are shown in the form of boxplots which indicate the significant (p-value < 0.05) or insignificant (p-value > 0.05) differences between the pair of collectors. In all significant cases, the MDt collectors captures more than the BSNE versions.

## RESULTS AND DISCUSSION

Wind erosion is actually an important cause of land degradation worldwide. Therefore, more studies concerning this phenomenon are necessary in order to assist with setting policies and decision-making (Panagos *et al*., 2012; Borrelli *et al*., 2016).

Lozano *et al*. (2013) and Asensio *et al*. (2015b) suggested that bulk density tends to be reduced by organic enrichment effects, and increased by the accumulation of fine materials, which can affect physical soil crusting.

The mean soil characteristics recorded for Anthrosols, Leptosols, Arenosols and Cambisols in the study area are shown in Table 2. Four replicate samples were taken of each soil type. Surface stoniness is only high for LP and the average gravel content for the different soil types is 6.1% in AT, 37.3% in LP, 5.3% in AR and 47.7% in CM.

By using a wind tunnel, it was possible to focus on the losses and deposits that occur in a micro plot which the laser scanner is able to detect. The results for the four types of soil blown into the wind tunnel at the same artificially generated wind speed (7.2 m s$^{1}$) are shown in Table 3.

**Table 2.** Soils characteristics

| Sample | Very C. Sand | Coarse Sand | Medium Sand | Fine Sand | Very F. Sand | Coarse Silt | Fine Silt | Clay | O.C. | $CO_3^=$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | (%) | | | | | | | | | |
| AT | 5.8 ± 0.4 | 11.1 ± 0.9 | 22.6 ± 2.4 | 31.2 ± 2.6 | 20.0 ± 1.9 | 0.4 ± 0.2 | 2.2 ± 0.7 | 6.7 ± 0.9 | 1.70 ± 0.21 | 23 ± 3 |
| LP | 15.1 ± 1.5 | 14.9 ± 1.2 | 22.4 ± 2.7 | 24.7 ± 1.7 | 5.2 ± 0.3 | 6.4 ± 0.7 | 2.6 ± 0.5 | 8.7 ± 1.2 | 3.54 ± 0.47 | 19 ± 4 |
| AR | 0.3 ± 0.2 | 6.1 ± 0.4 | 48.8 ± 3.6 | 38.2 ± 2.9 | 2.9 ± 0.3 | 0.5 ± 0.3 | 0.2 ± 0.2 | 3.0 ± 0.7 | 1.25 ± 0.09 | 0 ± 0 |
| CM | 0.0 ± 0.2 | 8.2 ± 0.6 | 7.6 ± 0.5 | 8.9 ± 0.7 | 20.2 ± 2.3 | 28.4 ± 1.8 | 7.9 ± 1.1 | 18.8 ± 2.0 | 1.82 ± 0.18 | 20 ± 2 |

Data are means ± standard deviation (n = 4).

**Table 3.** Wind erosion found in the wind tunnel, after four replicates (A to D)

| Sample | Lost (Laser scanner) (mm) | | | | | Bulk density (t m$^{-3}$) | Wind erosion (Tunnel) (t ha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | Average | | |
| AT | 0.87 | 0.96 | 0.82 | 1.02 | 0.92 | 1.24 | 11.41 |
| LP | 0.78 | 0.73 | 0.67 | 0.87 | 0.76 | 1.36 | 10.34 |
| AR | 0.22 | 0.21 | 0.23 | 0.22 | 0.22 | 1.28 | 2.82 |
| CM | 1.37 | 1.66 | 1.39 | 1.78 | 1.55 | 1.35 | 20.93 |

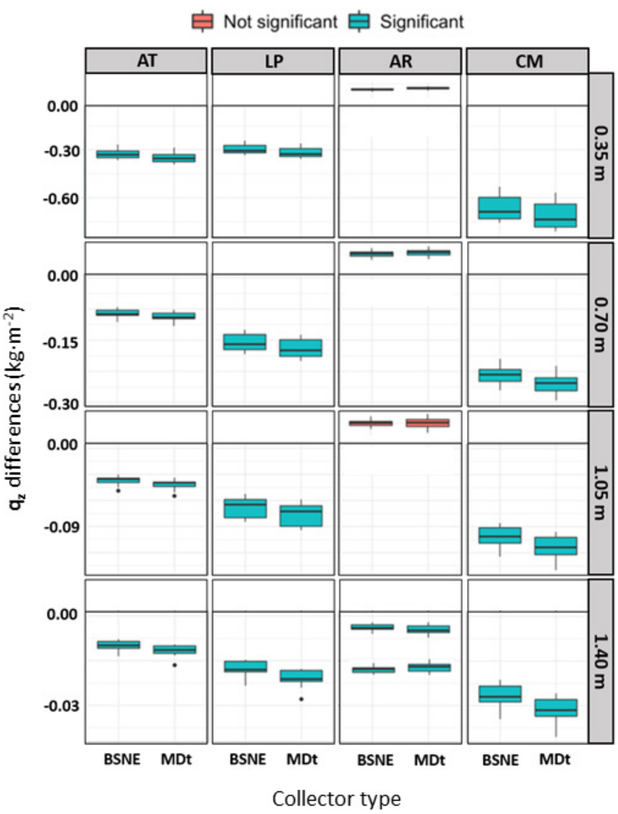


**Fig. 4.** Comparison of differences in $q_z$ between BSNE and MDt collectors.

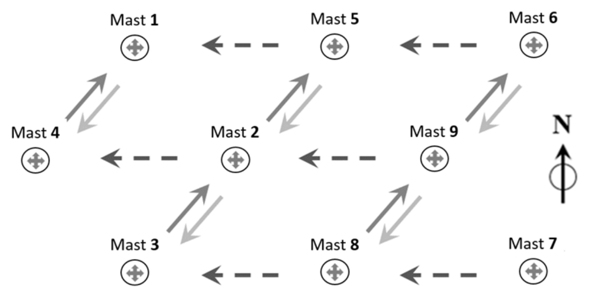


**Fig. 5.** Masts locations with different kind of arrows showing main wind directions.

The Anthrosols were sampled from a highly tilled orchard with a low silt and clay content. Measurements took place right after tilling. The Leptosols were sampled from unploughed areas with little protection from the direct impact of wind. Arenosols sampled from along the coast had a low very fine sand, silt and clay content where vegetation had an important protective role. Finally, the Cambisols appeared to be crusted in an olive orchard. After tillage, Cambisols are highly erodible by wind, but according to Asensio *et al.* (2016), with regard to Cambisols, the physical crust tends to recover within 10 to 12 days. For that particular wind tunnel study, the average soil loss was found to be over six times higher in recently tilled Cambisols than for crusted versions of the soil.

The methodology adopted which made use of BSNE and MDt collectors made an in-depth wind erosion study possible. The sediment fluxes on nine masts had both collector types to determine each soil typology at different heights. Figure 4 shows the results of a comparison between the two collector types. The boxplots in red indicate no significant differences (p-value > 0.05) between the pair of collectors.

**Table 4.** Mast numbers where values differed on each soil type

| Sample | Main wind direction | Differences in sediment flux captured by masts (windward – leeward) | | | | | |
|---|---|---|---|---|---|---|---|
| AT, LP | from NE | M1-M4 | M5-M2 | M6-M9 | M2-M3 | M9-M8 | |
| AR | from E | M6-M5 | M9-M2 | M7-M8 | M5-M1 | M2-M4 | M8-M3 |
| CM | from SW | M4-M1 | M3-M2 | M2-M5 | M8-M9 | M9-M6 | |

**Table 5.** Sediment transport rate balance

| Sample | $Q_r$ balance (kg m$^{-1}$) | |
|---|---|---|
| | BSNE | MDt |
| AT | -0.019 | -0.017 |
| LP | -0.014 | -0.001 |
| AR | 0.001 | 0.005 |
| CM | -0.011 | -0.036 |

In most cases, the differences in the amount captured are statistically significant, and in all significant cases, MDt captured more material than the BSNE collectors.

According to the data provided by the collectors, the freshly ploughed Cambisols produced the highest emission flux, which is in agreement with other experimental studies (Marzen *et al*., 2019). Tilling leads to a partial breakdown of crust and clods, thereby generating a comparably high proportion of noncohesive substrate of fine fractions which are the most easily erodible by wind. An organic matter content which is not particularly high and the mechanical reduction of aggregate sizes through tilling decreases aggregate stability and further increases the amount of wind-erodible sediment on the surface, particularly under dry soil conditions. This situation is aggravated by long droughts. Since wind erosion leads to a sorting of the soil material predominantly involving the gradual removal of the finest grain sizes, silt and clay, including a high proportion of soil nutrients (Katra *et al*., 2016), it is a severe threat to soil management.

As the main wind direction over each soil type was different (Fig. 5), a dataset composed of the differences between the sampling points located windward and leeward relative to the prevailing wind direction (Table 4). Thus, positive differences indicated gains and negative ones pointed to a loss of material.

As a result, the estimated sediment transport rate balance for the nine masts with both collector types for each soil typology are shown in Table 5. This clearly indicated

**Table 6.** Total mass transport ($Q_t$)

| Sample | Vaned mast | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Average |
| | | | | | $Q_t$ (BSNE) (kg) | | | | | |
| AT | 15.54 | 18.45 | 19.73 | 17.80 | 17.49 | 17.20 | 20.58 | 19.86 | 18.51 | 18.35 |
| LP | 20.83 | 24.82 | 26.85 | 24.26 | 28.62 | 23.24 | 27.73 | 26.81 | 20.49 | 24.8 5 |
| AR | 7.71 | 8.262 | 8.83 | 7.615 | 7.573 | 8.430 | 8.002 | 9.019 | 8.142 | 8.175 |
| CM | 49.43 | 43.59 | 39.14 | 55.02 | 46.57 | 52.93 | 42.43 | 50.72 | 51.90 | 47.97 |
| | | | | | $Q_t$ (MDt) (kg) | | | | | |
| AT | 21.47 | 20.02 | 22.77 | 22.75 | 19.94 | 18.30 | 23.41 | 19.97 | 17.99 | 20.74 |
| LP | 22.44 | 26.78 | 19.38 | 25.80 | 19.08 | 24.97 | 24.13 | 21.79 | 25.03 | 23.27 |
| AR | 7.404 | 7.109 | 6.195 | 7.437 | 7.746 | 8.247 | 6.5511 | 7.890 | 8.164 | 7.416 |
| CM | 44.86 | 40.88 | 37.59 | 53.24 | 49.19 | 51.25 | 38.98 | 42.33 | 50.36 | 45.41 |

a deposition on Arenosols compared to a loss for the rest of the soils tested. Finally, the total mass transport results are shown in Table 6.

After evaluating sediment transport rates and determining their balance, the Arenosols data indicated that with regard to these soils, material was deposited rather than lost. Data from wind tunnel evaluation showed low Arenosols loss, as this device is a closed structure and cannot detect windward deposition. However, in front of it, the wind tunnel rapidly provided accurate replicable data, mainly concerning soil wind erosion. In addition, a comparison of total mass transport for each soil type from the collectors and wind erosion as reported by the wind tunnel tests showed a high degree of linear correlation ($R^2 = 0.933$ for BSNE-Tunnel data and $R^2 = 0.978$ for MDt-Tunnel data).

## CONCLUSIONS

1. A wind tunnel is a closed device in which there is no entry of windward deposits. It is mainly used to evaluate the wind erodibility of the soil, more than overall erosion, although the results produced maintain a very close correlation with the data from the particle collectors, showing a higher loss for Cambisols and a lower one for Arenosols.

2. The tunnel provides much faster results. However, with the collectors, the general loss or deposition of particles can be determined, and this is not detectable on a larger scale by the tunnel results.

3. On the other hand, the new multidirectional trap collectors are very efficient and easily manufactured by an industrial 3D printer from thermoplastic filaments, it is therefore a promising technology, which must be subjected to continued testing.

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**Conflict of interest:** The authors declare no conflict of interest.

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## 5.2. ARTÍCULO 2:

Guerrero, R.; Valenzuela, J.L.; Chamizo, S.; Torres, J.L.; Asensio, C. 2021. *Multidirectional traps as a new assessment system of soil wind erosion. SCIENTIA AGRICOLA, 79 (4): 1-7* (doi.org/10.1590/1678-992X-2020-0342).

RESUMEN:

Probamos un nuevo tipo de colector de partículas transportado por el viento (trampas multidireccionales, MDt) en el sureste de España para analizar el movimiento de partículas en tres tipos de suelo diferentes. Los colectores MDt son fáciles de fabricar a partir de filamentos termoplásticos con una impresora industrial 3D. Los recolectores probados fueron muy eficientes. Nuestra investigación se llevó a cabo en Calcisoles sin cultivar y en Fluvisoles y Luvisoles con cultivos de naranjos y olivos, respectivamente. Los resultados de los registros de nueve mástiles, con cuatro colectores de MDt a diferentes alturas, sobre Calcisoles, Fluvisoles y Luvisoles se compararon con la fracción erosionable (FE) de estos suelos por el viento, estimada empíricamente y con sus tasas de erosión calculadas en un túnel de viento de diseño propio, que incluye un escáner láser incorporado. Estos nuevos colectores pueden diferenciar los sedimentos captados por su dirección de origen y disponerse en una red de mástiles, lo que permite distinguir la pérdida o deposición total de partículas, que no es detectable con el túnel de viento debido a la escala de trabajo y la ausencia de depósitos a barlovento, ya que es un dispositivo cerrado. La comparación de la FE calculada y la masa total de partículas transportadas registrada por los colectores MDt, mostró una muy buena correlación ($R^2$ = 0.914) con una relación aún mejor entre los resultados del túnel de viento y los colectores (R2 = 0.974). La precisión, financiación y el tiempo de ejecución requeridos son importantes para determinar el uso de un dispositivo u otro. Concluimos que el collector MDt muestra un buen potencial.

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Scientia Agricola
Research Article

# Multidirectional traps as a new assessment system of soil wind erosion

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**ABSTRACT**: We tested a new type of wind-transported particle collector (multidirectional traps, MDt) in southeast Spain to forecast particle movement in three different soil types. The MDt collectors are easy to manufacture from thermoplastic filaments with an industrial 3D printer. The collectors tested were very efficient. Our research was carried out on unplowed Calcisols and on orange and olive-cropped Fluvisols and Luvisols, respectively. The results from the logs of nine vaned masts, each with four MDt collectors at different heights, on Calcisols, Fluvisols and Luvisols were compared with the wind erodible fraction of these soils (EF) empirically estimated and with their erosion rates calculated in a wind tunnel of our own design with a built-in laser scanner. These new collectors can differentiate the collected sediments by their direction of origin and arranged in a network of masts, enabling to distinguish overall particle loss or deposition, which is not detectable with the wind tunnel due to the work scale and no windward deposits, as it is a closed device. Comparison of the calculated EF and the total mass of transported particles recorded by the MDt collectors showed very good correlation ($R^2$ = 0.9144) with an even better relationship between the results of the wind tunnel and collectors ($R^2$ = 0.9741). Required precision, financing, and execution time are important in determining the use of the device. We conclude that this device shows good potential.
**Keywords**: semi-arid environment, wind tunnel, dust collectors, soil crusts

## Introduction

Wind erosion is a major cause of land degradation worldwide. Therefore, more studies are needed to aid in policy and decision-making (Panagos et al., 2012). The decrease in soil compaction, in its vegetation cover, and in its OM content increases the risk of wind erosion of the soil (Novara et al., 2011; Prosdocimi et al., 2016; Arjmand Sajjadi and Mahmoodabadi, 2015). Climate also influences erosion, making some regions more affected by these processes (Borrelli et al., 2016; Weber et al., 2017). Obviously, human activity in cultivated areas has a very important role.

Analyzing Mediterranean cultivation systems, Benlhabib et al. (2014) recommended sustainable cultivation technologies, which showed a significantly positive effect on productivity and yield. Colazo and Buschiazzo (2010, 2015) and Zobeck et al. (2013) confirmed that the crop increased the wind-erodible fraction (EF) of the soil and reduced the stability of dry aggregates in medium-texture soils, which weakened soil structure in addition to causing OM loss and breakdown of aggregates. Fryrear et al. (1994) proposed the use of a multiple regression equation for calculating EF, when a rotary sieve is not available.

There are many models of wind tunnels for field simulations. Some specific components, being a laser scanner the most important, have been added to our prototype (Giménez et al., 2019). The built-in laser scanner shows changes in the micro-relief and allows quick estimates of the volume of eroded soil. Many samplers have also been developed to determine the amount of material carried by the wind (Goossens et al., 2000). According to Zobeck et al. (2003), the choice of collector type depends on the study to be carried out, precision required, and financial resources. Models available vary in size, shape, type of material to be quantified, and collection efficiency. Feras et al. (2008) demonstrated that the efficiency of the sediment trap depends mainly on particle size and wind speed. Mendez et al. (2011) and Goossens and Buck (2012) found that efficiency increased as particle size decreased and wind speed increased. The placing of traps at different heights allows measuring vertical sediment flow (Basaran et al., 2011). We used new wind-borne particle collectors, called multidirectional traps (MDt), over non-plowed Calcisols with little coverage (around 5 %) and over orange and olive-cropped Fluvisols and Luvisols with coverages around 30 and 20 %, respectively. The collectors were built from thermoplastic filaments, adequate to resist the impacts of wind-borne particles.

Our objectives here were to study the amount of material lost by the wind action under the same conditions and by different methods, in different representative soil types in southeast Spain, as well as to compare the differences between the eroded material reported by traditional methods and a new technique, evaluating the results.

## Materials and Methods

The study site is located in the province of Almería, southeast Spain (Figure 1). The climate is semi-arid Mediterranean with an average annual temperature of 18.7 °C and rainfall of 256 mm. The dominant geological material belongs to a Miocene sedimentary series. Natural plant communities are isolated native shrubs, but today intense horticultural and tree crops are also grown. According to the IUSS WRB Working Group (2015), the soils studied are haplic Calcisol (CL), aric-gypsiric Fluvisol (FL) and hapli-chromic Luvisol (LV).

Table 1 shows the site, sampling date, average wind speed and direction, average temperature and relative humidity of the soils studied. In all cases, there were wind gusts over 15 m $s^{-1}$.

Meteorological records were taken from the automatic meteorological station network of the Andalusian Agricultural and Fisheries Research and Education Institute (IFAPA) (http://www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/servlet/FrontController" http://www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/servlet/FrontController), an institution of the Junta de Andalucía (Andalusian regional government).

Four replicate samples from the top 5 cm of soils were taken and analyzed. Texture data were found by the Robinson pipet method. Organic carbon content was analyzed using the Walkley-Black wet digestion method. Gas volumetry was used to determine the carbonate content. To determine the bulk density, 100-$cm^3$ cylinders were used for the dry weight of the sample to be referred to by cylinder volume.

The wind-erodible fraction of the soils was calculated following Eq. (1) of Fryrear et al. (1994):

$$EF = 29.09 + 0.31 \text{ sand} + 0.17 \text{ silt} + 0.33 \text{ sand/clay} - 2.59 \text{ organic matter} - 0.95 \text{ CaCO}_3 \quad (1)$$

where: all variables, including wind-erodible fraction (EF) of the soils, are expressed in %.

Wind erosion was monitored in a wind tunnel to study the effects of a wind stream at constant speed on the soil surface (Figure 2A). The wind tunnel has a telescopic structure. The middle section is equipped with a NextEngine Desktop 3D laser scanner to find changes in the micro-relief first and later in the volume of eroded soil

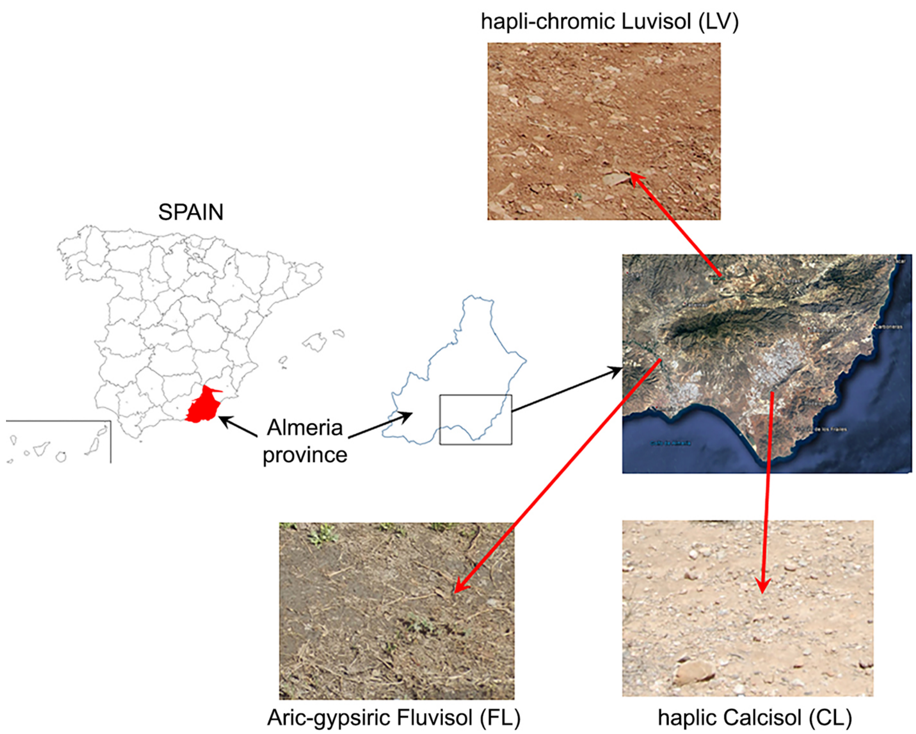


**Figure 1** – Location of soils studied.

**Table 1** – Coordinates, altitude, sampling date, and climatic characteristics of the soils studied.

| SOIL | Location | | | Date | Averaged wind speed | Averaged direction | Averaged temperature | Averaged relative humidity |
|---|---|---|---|---|---|---|---|---|
| | Coordinates | | Altitude | | | | | |
| | | | (m) a.s.l. | | m $s^{-1}$ | ° | °C | % |
| CL | 36°51’41.72” N | 2°16’26.04” W | 91 | 31/05/2019 | 3.0 | 86.1 | 21.6 | 43 |
| FL | 36°57’58.23” N | 2°28’9.58” W | 164 | 27/03/2019 | 2.6 | 73.4 | 10.1 | 57 |
| LV | 37°06’53.85” N | 2°18’5.63” W | 573 | 23/01/2019 | 4.8 | 239.3 | 11.1 | 52 |

CL = Calcisols; FL = Fluvisols; LV = Luvisols.

(Asensio et al., 2016). Following the criteria of Fister and Ries (2009), the wind tunnel experiments lasted 10 min at a wind speed of 7.6 m $s^{-1}$ monitored at a height of 70 cm. This wind speed is the maximum daily average recorded over the last 20 years by the agroclimatic stations in our region. The soil surface was scanned before and after wind simulation, in each case, by using high definition and macro mode. These scans provided two point clouds for each scatterplot, from which two digital terrain models (DTM) were automatically generated with a resolution of 0.1 × 0.1 cm. The eroded volume of the soil was estimated as the difference between the DTMs. Therefore, knowing the bulk density of each soil, the amount of soil lost could be estimated (Asensio et al., 2016). In this device, the air stream speed is a reliably reproducible fixed parameter. Four different plots were chosen on each soil type to reflect the natural variability of the test plots for the collected data.

In addition to the wind tunnel, we used our own patented collectors (Asensio et al., 2015a) manufactured by an industrial 3D printer from a glycol-modified ethylene polyterephthalate (PETg) thermoplastic filament. PETg is a tough material, ideal for objects subjected to mechanical stress, hard, flexible and resistant. Figure 2B shows a diagram of the design of this new collector, which we call a multidirectional trap (MDt). The air with the material enters them through a rectangular 2 × 5 cm opening and a grill inside modifies its movement. The material is deposited in a removable structure, with a fixed, ring-shaped base. There are eight north-facing compartments in the ring, which can differentiate the captured materials by the direction of origin. Each of these collectors is attached to a vaned mast (Figure 2C). According to Asensio et al. (2015b), the MDt collector efficacy (74 %) is higher for fine grain sizes. Each experiment with the collectors lasted for 24 consecutive hours.

A network of nine vaned masts was mounted with the MDt traps placed at 0.35, 0.70, 1.05 and 1.40 m heights to ensure that their inlets always faced the main wind direction. The rotating masts were spaced 50 m apart to avoid interference from the others. This was performed in each soil type. Figure 3 shows the masts distribution on an olive-cropped Luvisol.

As our collectors were placed at different heights on the mast starting at 0.35 m, the difference in the rate of soil lost with distance from the soil surface had to be measured empirically using a mathematical model that predicts the amount of sediment on the soil surface. Sediment flux (qz, kg $m^{-2}$) at each trap height (z, m) was found by Eq. (2).

$$q_z = \frac{m}{A} \quad (2)$$

where: $m$ – sediment weight (kg) captured by each collector at a given height; $A$ – inlet area ($m^2$) of a collector.

Then, sediment flux was predicted ($q_{z.\exp}$, kg $m^{-2}$) by an exponential equation for every amount modelled in Eq. (3):

$$q_{z.\exp} = q_0.e^{-\alpha z} \quad (3)$$

where: $q_o$ – amount of sediment modelled at $z = 0$ (kg $m^{-2}$); α – slope factor of exponential regression equation (m).

The sediment transport rate (Qr, kg $m^{-1}$) was then determined by integrating $q_{z.\exp}$ (kg $m^{-1}$) predicted using Eq. (4):

$$Q_r = \int_0^h q_{z.\exp} dz \quad (4)$$

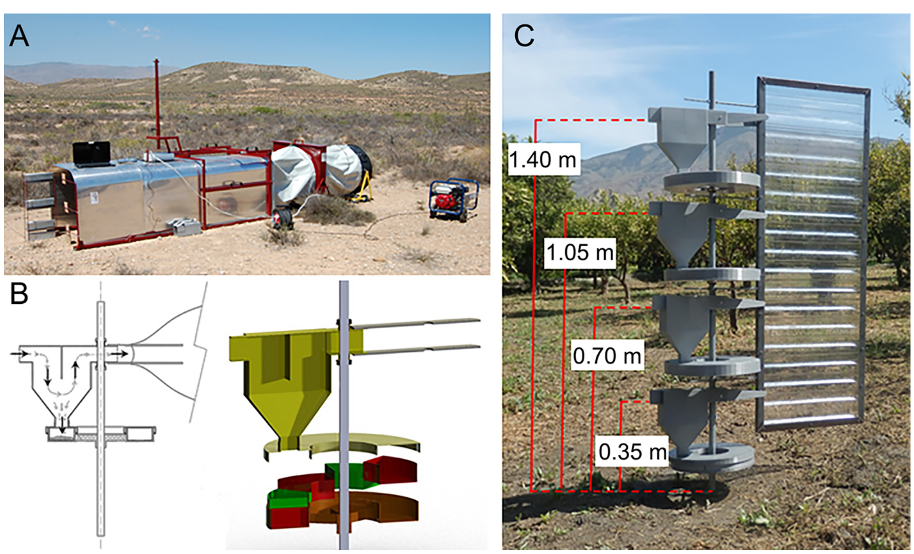


**Figure 2** – A) Wind tunnel on a Calcisol; B) Schemes of MDt collectors; C) Mast and wind vane with MDt collectors on a Fluvisol.

where: $h$ – maximum particle transportation height (m) recorded.

Total mass transport ($Q_t$, kg) was calculated by Eq. (5):

$$Q_t = \left(\frac{Q_r}{\eta}\right) L \quad (5)$$

where: η - trap efficiency; $L$ - plot width.

The amount of material lost (or deposited) was calculated as the difference in the sediment flux or sediment transport rate between sampling points located windward and leeward in the prevailing wind direction. Thus, positive differences indicated gains, while negative differences referred to material loss.

A non-parametric Wilcoxon signed-rank test was performed to determine whether the amount of material captured at the same heights by the collectors differed. We compared the total amount collected and the amount collected by the windward oriented compartment, for each soil type.

## Results

Soil characteristics recorded for Calcisols, Fluvisols, and Luvisols in the study site are shown in Table 2.

The soil surfaces are not highly stony, except on CL, and the average gravel content for the different soil types is 22 % in CL, 19 % in FL, and 43 % in LV.

The wind tunnel allowed to focus on losses and deposits only within a microplot that the laser scanner can detect. Table 3 shows the results for the three soil types blown into the wind tunnel at the same artificially generated wind speed (7.2 m s$^{-1}$). It also includes the average wind-erodible fraction of the soils, following Fryrear et al. (1994).

As described above, the MDt collectors (Figures 2B and 2C) allowed to differentiate the direction the particles trapped coming from with their internal compartments (inside the ring structure). Figure 4 shows sediment fluxes on the MDt collector estimated for each soil type. We determined sediment flux data from the windward compartments recorded and the total amount corresponding to the whole collector (sum of all compartments). Sediment transport rates were found by integration of the exponential Eq. (3).

As the main wind direction for each soil type was different (Figure 5), we compiled a dataset of the differences between the sampling points located upwind

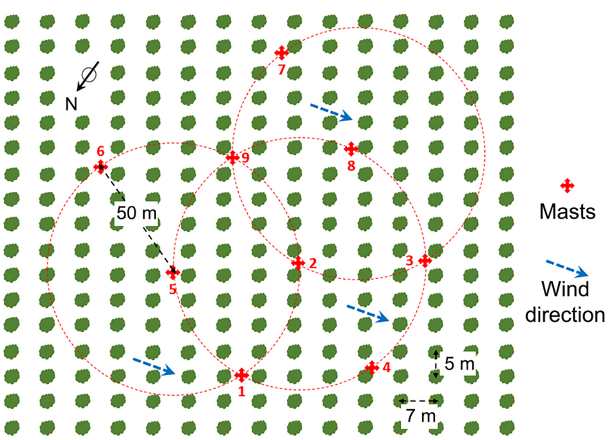


**Figure 3** – Example of masts distribution on a Fluvisol.

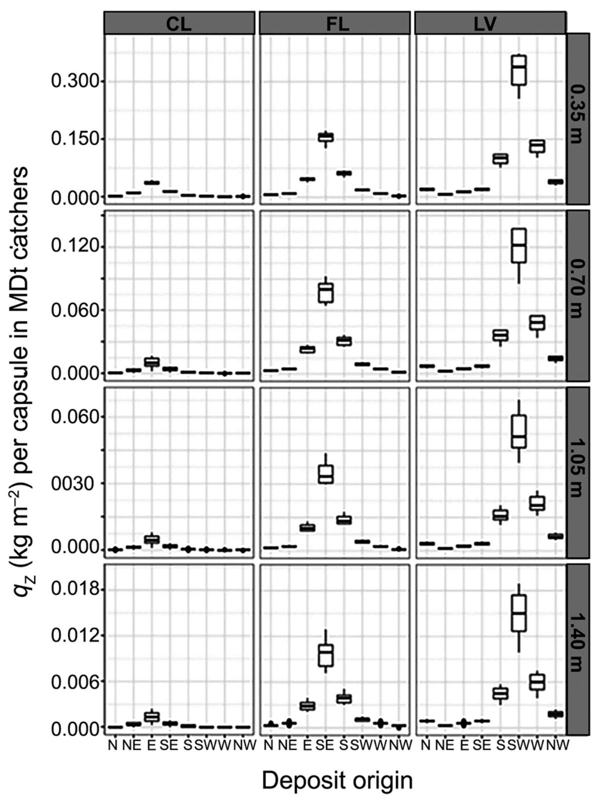


**Figure 4** – Average sediment fluxes by soil type, collector height, and directional compartment.

**Table 2** – Soils characteristics.

| SOIL | VC Sand | Coarse Sand | Medium Sand | Fine Sand | VF Sand | Coarse Silt | Fine Silt | Clay | OM | $CO_3^{=}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | g kg$^{-1}$ | | | | | | | | | % |
| CL | 60 ± 5 | 61 ± 4 | 95 ± 7 | 193 ± 16 | 225 ± 18 | 75 ± 8 | 117 ± 11 | 174 ± 14 | 15.5 ± 1.9 | 40 ± 3 |
| FL | 21 ± 4 | 52 ± 5 | 70 ± 6 | 87 ± 9 | 155 ± 12 | 220 ± 19 | 183 ± 17 | 212 ± 23 | 36.5 ± 5.7 | 24 ± 2 |
| LV | 0 ± 1 | 55 ± 4 | 62 ± 3 | 89 ± 8 | 259 ± 22 | 267 ± 21 | 63 ± 6 | 204 ± 26 | 49.0 ± 5.0 | 2 ± 1 |

VC = Very coarse; VF = Very fine; OM = Organic matter; CL = Calcisols; FL = Fluvisols; LV = Luvisols.

and leeward in the prevailing wind direction (Table 4). Thus, positive differences indicated gains and negative differences showed a loss of material.

Table 5 shows the sediment transport rate balance, where the MDt collectors clearly indicate deposition in Calcisols compared to loss in the other soils tested.

Finally, Table 6 shows the results for total mass transport.

## Discussion

Calcisols appeared in unplowed areas with little protection from the direct wind impact. Trees (orange and olive orchards, respectively) protected both Fluvisols and Luvisols and both soils were crusted, but crusting was more significant in the Luvisols. Immediately after tillage, Luvisols are highly erodible by wind, but according to Asensio et al. (2016), their physical crust tends to recover within 10-12 days. In the wind tunnel study, the average soil loss was over 14 folds higher in recently tilled Luvisols than in crusted soils.

**Table 3** – Wind erosion in the wind tunnel, after four replicates (A to D).

| SOIL | Lost (Laser scanner) (mm) | | | | | Bulk density | Wind erosion (Tunnel) | EF |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | Average | | | |
| | | | | | | t m$^{-3}$ | t ha$^{-1}$ | % |
| CL | 0.11 | 0.17 | 0.10 | 0.15 | 0.13 | 1.41 | 1.83 | 11 |
| FL | 0.69 | 0.84 | 0.71 | 0.95 | 0.8 | 1.29 | 10.32 | 16 |
| LV | 1.02 | 1.45 | 1.14 | 1.50 | 1.28 | 1.22 | 15.62 | 35 |

EF = Wind erodible fraction; CL = Calcisols; FL = Fluvisols; LV = Luvisols.

According to the collector data, the freshly plowed Luvisols produced the highest emission flux, in agreement with other experimental studies (Marzen et al., 2019). Tillage led to a partial breakdown of crust and clods, generating a comparably high proportion of incoherent substrate of the fine fractions most easily erodible by wind. As the OM was not very high, mechanical reduction of aggregate sizes by tilling decreased the aggregate stability and further increased the amount of wind-erodible sediment on the soil surface, mainly under dry soil conditions (Colazo and Buschiazzo, 2010, 2015). The long drought aggravated the situation. Wind erosion leads to the sorting of soil material and gradually removes predominantly the finest grain sizes, silt and clay, including a high proportion of soil nutrients (Katra et al., 2016); therefore, wind erosion is a severe threat to soil management, for both 5-year old orange (FL) and 8-year-old olive (LV) orchards.

Figure 6 shows the boxplots of differences between material trapped on windward compartments and total amount of material trapped by the MDt collectors for each soil type. If one set of collectors systematically captures more than the other sets, the entire boxplot is above or below 0. The results of the statistical test applied indicate that, in most cases, the differences found are not statistically significant ($p$-value > 0.05). For Calcisols, the test detected significant differences ($p$-value < 0.05) mainly in windward collectors. Future experiments need to analyze the influence in high carbonate content and its aggregating role in this soil type, in addition to the consequences of its very stony surface.

**Table 4** – Mast numbers where values differed on each soil type.

| SOIL | Main wind direction | Differences in sediment flux catched by masts | | | | | |
|---|---|---|---|---|---|---|---|
| CL, FL | from East | M 6 – M 5 | M 9 – M 2 | M 7 – M 8 | M 5 – M 1 | M 2 – M 4 | M 8 – M 3 |
| LV | from Southwest | M 4 – M 1 | M 3 – M 2 | M 2 – M 5 | M 8 – M 9 | M 9 – M 6 | |

CL = Calcisols; FL = Fluvisols; LV = Luvisols.

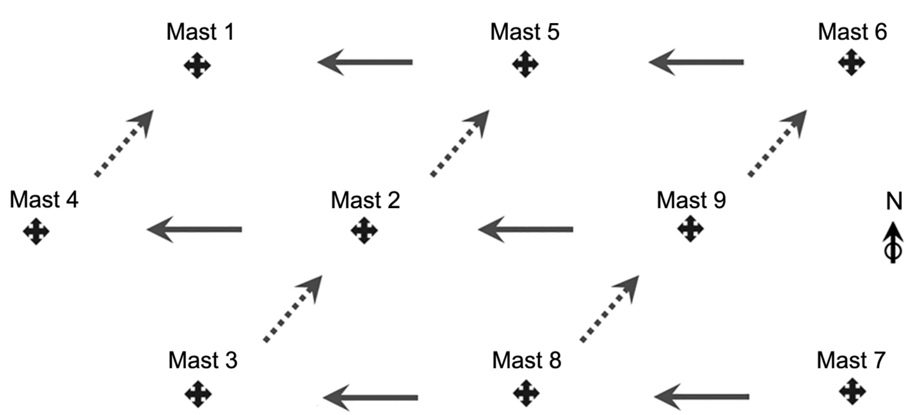


**Figure 5** – Mast locations with different arrows showing main wind directions.

Evaluation of Calcisol sediment transport rates and their balance indicated that material was being deposited not lost in this soil. Data from wind tunnel evaluation showed low Calcisol loss. The device is a closed structure and cannot detect windward deposition. However, the wind tunnel rapidly provided replicable accurate data, mainly on soil wind erodibility.

Finally, a comparison of total mass transport of each soil type from collectors and the calculated wind erodible fraction showed very good linear correlation ($R^2$ = 0.9144), which was better than the wind erosion reported by the wind tunnel ($R^2$ = 0.9741).

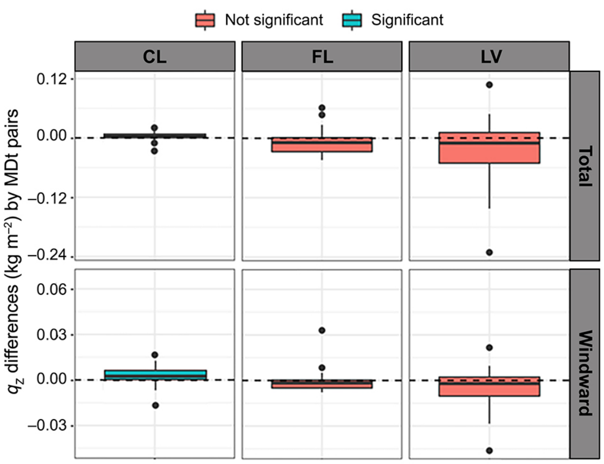


**Figure 6** – Comparison of sediment flux at each trap height (qz) differences between MDt collectors (total and windward origin) and soil types.

**Table 5** – Sediment transport rate balance.

| SOIL | $Q_r$ balance | |
|---|---|---|
| | MDt windward | MDt total |
| CL | 0.0006 | 0.0014 |
| FL | –0.0497 | –0.0782 |
| LV | –0.0260 | –0.0465 |

CL = Calcisols; FL = Fluvisols; LV = Luvisols.

**Table 6** – Total mass transport ($Q_t$).

| SOIL | $Q_t$ (MDt windward) (kg) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Average |
| CL | 2.1892 | 2.3268 | 2.7776 | 1.9556 | 3.1625 | 2.4923 | 1.9254 | 2.9917 | 2.7608 | 2.5091 |
| FL | 11.3326 | 10.7330 | 9.7798 | 12.8988 | 12.0633 | 12.5803 | 9.7422 | 10.8261 | 12.5178 | 11.386 |
| LV | 23.5806 | 19.0067 | 19.8709 | 27.7675 | 26.9378 | 28.0535 | 17.3698 | 22.1445 | 22.1445 | 22.9862 |
| SOIL | $Q_t$ (MDt total) (kg) | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Average |
| CL | 4.1592 | 4.2747 | 4.7432 | 3.4210 | 5.3093 | 4.3949 | 3.6414 | 5.0959 | 4.8721 | 4.4346 |
| FL | 21.5343 | 20.7062 | 18.5467 | 24.7000 | 23.2189 | 24.2446 | 19.9898 | 20.7871 | 23.9254 | 21.9614 |
| LV | 41.1931 | 33.2460 | 34.8096 | 48.5924 | 47.4469 | 49.2885 | 32.2756 | 38.8311 | 46.3171 | 41.3334 |

CL = Calcisols; FL = Fluvisols; LV = Luvisols.

## Conclusion

A wind tunnel is a closed device in which there is no entry of windward deposits. It mainly evaluates wind erodibility of the soil, more than overall erosion, although it keeps a very good correlation with data from the particle collectors. The tunnel provides much faster, same-day results. However, the collectors allow to determine the general loss or deposition of particles, which is not detectable on a larger scale with the tunnel. On the other hand, the new MDt collectors are very efficient, easily and quickly manufactured by an industrial 3D printer from thermoplastic filaments and cheap, if they need to be replaced. They are unique devices for evaluating captured wind-borne particles in relation to their direction of origin; however, they require a longer evaluation time. The choice for one or another method depends on the required precision, financing, and experiment execution time. We therefore think this device shows good potential, but further testing in future experiments is required.

## Authors' Contributions

**Conceptualization**: Asensio, C.; Valenzuela, J.L. **Data acquisition**: Guerrero, R.; Valenzuela, J.L.; Chamizo, S.; Torres, J.L.; Asensio, C. **Data analysis**: Guerrero, R.; Chamizo, S.; Torres, J.L. **Design of methodology**: Asensio, C.; Valenzuela, J.L. **Software development**: Guerrero, R.; Torres, J.L.; Asensio, C. **Writing and editing**: Guerrero, R.; Valenzuela, J.L.; Chamizo, S.; Torres, J.L.; Asensio, C.

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## 5.3. ARTÍCULO 3:

Guerrero, R.; Valenzuela, J.L.; Monterroso, A.I.; Asensio, C. 2021. *Impact of wind direction on erodibility of a hortic Anthrosol in southeastern Spain. AGRICULTURE, 11-589* (doi.org/10.3390/agriculture11070589).

RESUMEN:
Probamos un colector de partículas transportadas por el viento, de diseño propio, llamado trampa multidireccional (MDt), que es eficiente y con una fabricación fácil y económica, en Antrosoles inténsamente labrandos. Los resultados de los registros de mástiles con cuatro colectores de MDt a diferentes alturas, mostraron un claro predominio de los vientos del noreste y del sur. Después de analizar las tasas de transporte de sedimentos y su equilibrio, encontramos que los sedimentos del sur se estaban depositando en lugar de perderse. En las trampas superiores se capturaron una gran cantidad de filosilicatos, que son sedimentos altamente adhesivos y, por lo tanto, aumentan la agregación y disminuyen la erosionabilidad eólica del suelo. Además, son ricos en carbonato cálcico, principalmente calcita, que es un agregante potente y, por tanto, también disminuye su erosionabilidad por el viento. Los sedimentos del noreste, sin embargo, con casi el doble del transporte total de masa, contenían la mayor cantidad de cuarzo capturado, lo que promueve la abrasión y aumenta la erosionabilidad del suelo. Sin embargo, grandes cantidades de materia orgánica encontradas en sedimentos del NE condujeron a cierta agregación, lo que equilibra la cantidad de material perdido.

*agriculture*

*Article*

# Impact of Wind Direction on Erodibility of a Hortic Anthrosol in Southeastern Spain

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**Abstract:** We tested an efficient, easily and economically manufactured wind-transported particle collector of our own design, called a multidirectional trap (MDt), on fine-tilled Anthrosols. Results from the logs of nine vaned masts, each with four MDt collectors at different heights, showed a clear predominance of northeast and south winds. After analyzing sediment transport rates and their balance, we found that sediments from the south were being deposited rather than lost. A large amount of phyllosilicates, which are highly adhesive sediments, and therefore, increase aggregation, decreasing erodibility, were captured in the upper traps. Moreover, they are rich in calcium carbonate, mainly calcite, which is a powerful aggregate, and therefore, also decreases their wind erodibility. Sediments from the northeast, however, with almost double the total mass transport, contained the largest amount of captured quartz, promoting abrasion and increasing soil erodibility. Nevertheless, large amounts of organic matter found in sediments from the NE led to some aggregation, which balances material lost.

**Keywords:** wind erosion; aeolian sediments; soil loss; sediment traps

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## 1. Introduction

In arid and semi-arid areas, where winds are often strong and rainfall is scarce, wind erosion of soil causes agronomic, environmental, social and economic problems, impacting adversely on the population [1–4]. More studies in this area are therefore needed to aid in policy and decision-making [5].

In the absence of tillage, there is more natural vegetation and soil aggregation, which reduce soil loss from wind by slowing down wind speed, further increasing the capacity for capturing lost material [6,7]. Climate and the spatial and temporal variability in threshold wind velocity strongly influence the prediction of the amount and type of wind-blown particles [8,9]. In marginal areas where conservationist strategies are not applied, overgrazing, abandonment of tillage lands, deforestation, and so forth intensify wind erosion and generate considerable soil losses [10]. Cropping results in the loss of organic matter and breakdown of aggregates, which reduces the stability of dry aggregates in medium-textured soils and increases the wind-erodible fraction of the soil [11–13]. On the other hand, windy conditions promote soil nutrient loss and drying [14], both influenced by soil surface compaction.

Many dust-trap models have been developed for analyzing wind-blown material [15], but the Big Spring Number Eight (BSNE) [16] and the Modified Wilson and Cook (MWAC) [17] are the most widely used devices [18]. Collector entrapment efficiency depends on average wind-blown particle size. Previous field studies have shown that the efficiency of the BSNE increased with wind speed and smaller particle size [19]. Vertical sediment flow may be analyzed by using traps located at different heights [20]. In this study, we used our own new patented collector, called the Multidirectional trap (MDt), which incorporates several advantages and improvements. It is easily and economically manufactured and not only captures material transported by the wind from the surface of the soil but also differentiates it by direction of origin. By using a group of masts with these new collectors at different heights, overall particle loss or deposit in the study area can be determined, as well as their composition depending on origin. Thus, particles of known origin captured by the MDt may then be analyzed by X-ray diffraction, enabling fast, reliable identification and quantification of the crystalline phases present in a sample. This provides added value as wind-eroded mineral type and amount strongly influence the soil cation exchange capacity and hence soil fertility.

The objectives of this study were to study the amount of material deposited or lost by the wind from different directions, under the same conditions, in agricultural soil in Southeast Spain and to compare the qualitative and semi-quantitative differences between the soil minerals transported from different places and their effects on the soil studied.

## 2. Materials and Methods

The study area is located in Almeria province in southeastern Spain (36°58′26′′ N, 02°03′29′′ W), elevation 190 m ASL (Figure 1). The climate is semi-arid thermo-Mediterranean, with a mean annual temperature of 17.8 °C and mean annual precipitation of 249 mm, according to records for the last 20 years from the automatic meteorological station network of the Andalusian regional government. Lithological material is mainly a metamorphic basement separated by Pliocene and Quaternary sedimentation basins [21]. Natural plant communities are made up of isolated native shrubs surrounded by bare soil with colonization by annual plant species. Soils are deeply cropped hortic Anthrosols (ATh), with sandy texture, a weak medium subangular blocky structure and few gravel fragments (sampled 20 January 2020 on intensive commercial farming over 100 ha). We also analyzed (Figure 2) the surrounding eutrophic Leptosols (LPe) and haplic Calcisiols (CLh). By using a PCE-423 hot wire anemometer connected in parallel to a computer for 24 continuous hours, we established that the average wind speed was 4.0 m $s^{-1}$ with gusts of over 20 m $s^{-1}$ for no more than 3 min from NE and gusts of over 14 m $s^{-1}$ for no more than 4 min from S; temperature and relative humidity were 8.2 °C and 75.7%, respectively.

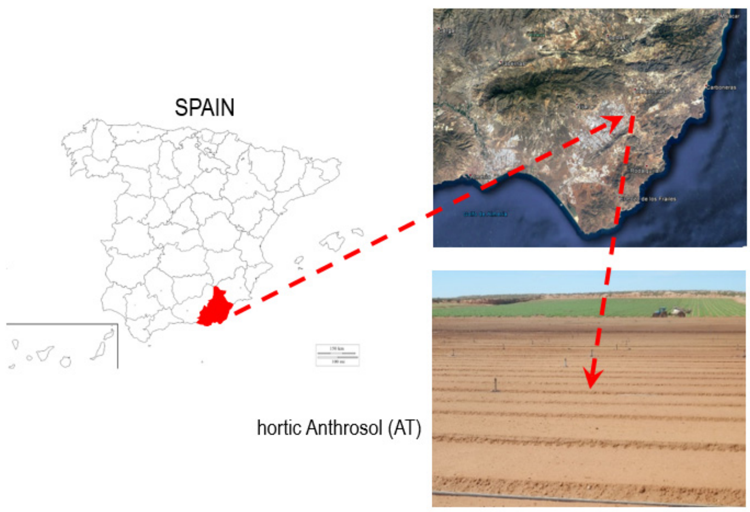


**Figure 1.** Location of study area.

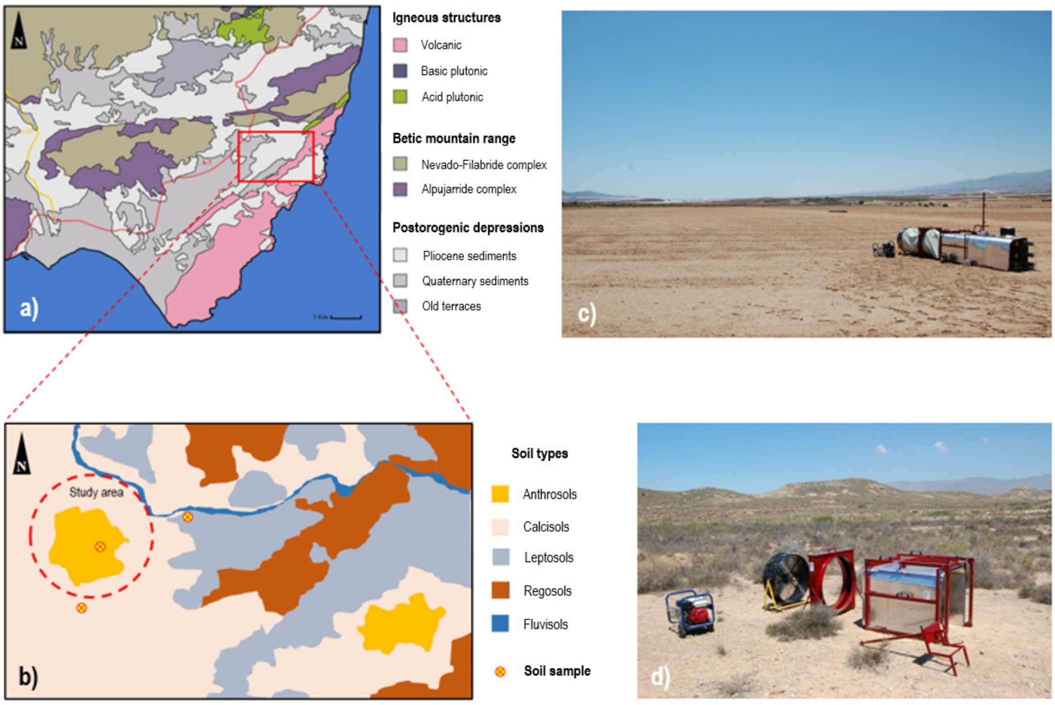


**Figure 2.** (**a**) Lithological location [21]; (**b**) soils map; (**c**) south view (from Anthrosols), with a wind tunnel of a former study; (**d**) northeast view.

Four replicate samples were taken from the top 5 cm of soils and analyzed, taking into account that wind erosion processes will fundamentally affect the most superficial part of the soils. Texture data were found by the Robinson pipet method. Organic matter content was obtained by applying the Van Bemmelen factor to organic carbon content analyzed with the Walkley–Black wet digestion method. Gas volumetry was used to determine the equivalent carbonate content.

The collectors used were our own patented Multidirectional traps (MDt) [22] fabricated with an industrial 3D printer from a glycol-modified ethylene polyterephthalate (PETg) thermoplastic filament. PETg is a tough, hard, resistant and flexible material, good characteristics for generating devices subjected to mechanical stress. Each of these collectors is attached to a vaned mast (Figure 3). The air with the transported material enters the collectors through a rectangular 2 × 5 cm window where a grill inside slows down its movement, causing the transported material to sediment in a removable structure with a fixed ring-shaped base. Eight north-facing compartments in the ring differentiate the direction of origin of the captured materials. Figure 3 shows a diagram of this new collector design. According to Asensio et al. [7], the efficiency of the MDt collector (74%) is higher for fine grain sizes. Experiments with these collectors were performed for 24 consecutive hours. A network of nine vaned masts was mounted with the MDt traps placed at 0.35, 070, 1.05 and 1.40 m heights, so their inlets faced the main wind direction at all times. The masts were located 50 m apart to avoid interfering with each other. Figure 3 shows field distribution of the masts. Experiments were carried out for 24 h.

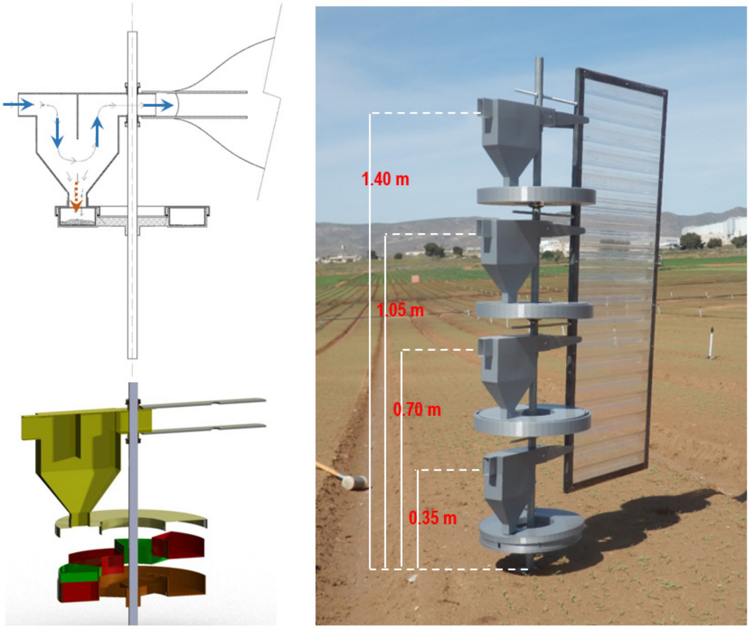


**Figure 3.** MDt collector schemes. Photo: mast and vane with collectors at different heights.

As the lowest collectors on the mast were placed at 0.35 m, the rate of soil lost from the ground had to be calculated empirically by using a mathematical model predicting sediment on the soil surface. Sediment flux ($q_z$, kg m$^{-2}$) at each trap height (z, m) was found by dividing the sediment weight (kg) caught by each collector at a given height by collector inlet area (0.001 m$^2$). Then, total sediment flux was calculated ($q_{z.exp}$, kg m$^{-2}$) by an exponential equation, and after integrating the total sediment flux, the sediment transport rate ($Qr$, kg m$^{-1}$) was calculated using Equation (1):

$$Q_r = \int_0^h q_0 \cdot e^{-\alpha z} dz \quad (1)$$

where:

*h*—maximum particle transportation height (m) recorded.

$q_o$—amount of sediment modeled at z = 0 (kg m$^{-2}$)

$\alpha$– slope factor of exponential regression equation (m).

Total mass transport ($Qt$, kg) was calculated by Equation (2):

$$Q_t = \left(\frac{Q_r}{\eta}\right) L \quad (2)$$

where:

$\eta$—trap efficiency

*L*—plot width.

The amount of material deposited or lost was calculated as the difference in the sediment transport rate between data from masts located windward and leeward in the main wind direction. Thus, negative differences indicated loss and positive, gains of material.

Although X-ray diffraction (XRD) is a semi-quantitative technique that can produce absolute errors, with standardized experimental conditions and interpretation, relative variations are reproducible. For powder samples, we used a "Davinci D8 Advance" diffractometer (Bruker Corporation, Madison, WI, USA) with copper radiation tube (CuK$_\alpha$, λ = 1.54 Å). The results were analyzed with the XPrep program and data were evaluated with the EVA program, both in the Diffract Evaluation 2.1 software package.

A non-parametric Wilcoxon signed-rank test was completed to determine differences in the amounts of sediments from different masts at the same height. We compared the total amount and the amount collected by the windward-oriented compartments.

## 3. Results

The means of the characteristics recorded for Anthrosols in the study area are shown in Table 1 as the average of four replicate samples. There is little surface stoniness, and gravel averages around 6%. Finely tilled Anthrosols have low silt and clay content. Sampling took place 5 days after tilling. Table 1 also recorded characteristics of surrounding windward soils (Leptosols and Calcisols), not always completely consolidated on the surface. Sediment flux per MDt collector compartment recorded by trap height and direction of origin are shown in Figure 4. Winds from the northeast and south are clearly predominant. Differences between material trapped in windward compartments and the total amount of material trapped by the MDt collectors at each height were not statistically significant ($p$-value > 0.05).

**Table 1.** Characteristics of soils and sediments in MDt compartments.

| Sample | Very Coarse Sand (2000–1000 μm) | Coarse Sand (1000–500 μm) | Medium Sand (500–250 μm) | Fine Sand (250–100 μm) | Very Fine Sand (100–50 μm) | Coarse Silt (50–20 μm) | Fine Silt (20–2 μm) | Clay (<2 μm) | O.M. | $CO_3^=$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | (g·kg$^{-1}$) | | | | | (%) |
| $LP_e$ | 15.1 | 13.8 | 21.9 | 23.7 | 6.2 | 5.3 | 3.8 | 10.2 | 43.4 | 18 |
| $AT_h$ | 5.6 | 11.4 | 23.2 | 29.2 | 20.3 | 0.7 | 2.4 | 7.2 | 29.0 | 24 |
| $CL_h$ | 6.6 | 6.2 | 9.3 | 18.8 | 22.1 | 7.1 | 12.3 | 17.6 | 16.8 | 41 |
| NE-35 | 0.1 | 0.7 | 5.8 | 11.9 | 30.3 | 18.3 | 11 | 21.9 | 42.4 | 16 |
| NE-70 | 0 | 0.2 | 1.2 | 6.3 | 36.1 | 20.5 | 13.5 | 22.2 | 43.4 | 15 |
| NE-105 | 0 | 0 | 0 | 0.5 | 37.2 | 21.3 | 15.4 | 25.6 | 39.1 | 13 |
| NE-140 | 0 | 0 | 0 | 0 | 18.3 | 23.8 | 26.6 | 31.3 | 34.7 | 11 |
| S-35 | 0 | 0.1 | 1.8 | 3.1 | 17.9 | 21.8 | 27 | 28.3 | 19.3 | 41 |
| S-70 | 0 | 0 | 0.4 | 2.7 | 19.9 | 23.6 | 27.5 | 25.9 | 16.9 | 39 |
| S-105 | 0 | 0 | 0 | 0 | 14.3 | 27.6 | 30.2 | 27.9 | 15.5 | 39 |
| S-140 | 0 | 0 | 0 | 0 | 7.6 | 29.8 | 32.4 | 30.2 | 14.7 | 37 |

Note: MDt compartment sediment labels include direction of origin and catchment height in cm.

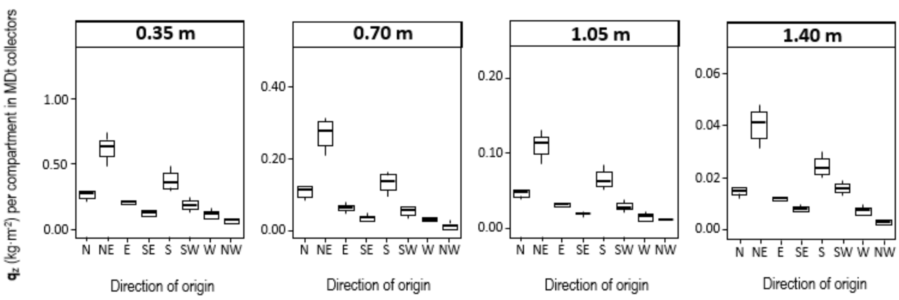


**Figure 4.** Sediment flux ($q_z$) per MDt collector compartment by trap height and direction of origin.

Table 1 shows the main characteristics for the most outstanding sediments in MDt compartments by direction of origin and catchment height, over Anthrosols.

As described above, the MDt collectors (Figure 3) are able to differentiate the direction the trapped particles come from by their internal ring compartments. An example of estimated sediment flux is shown graphically in Figure 5. This is useful for predicting soil particles transported by creep, in this example, 3.2463 kg m$^{-2}$, because the lowest trap height was 0.35 m. Sediment flux data were determined from the amount recorded in the windward compartments and the total amount corresponding to the whole collector (sum of all compartments). Sediment transport rates were found by integration. Even being aware of the limitations of the vertically integrated sediment flow estimation, we opted for this method because it will allow us to compare results with those obtained by other authors with the same method and similar climatic and edaphic conditions such as [20], in future works. Nevertheless, we assume that the sedimentary material transported into the lower layer is composed of very large grains of soil that cannot be transported very far and that a good estimate of the exported material can be assessed by considering only material transported above 0.35 cm. Thus, we use Equation 1 to integrate the flow of sediment not between 0 and 1.4 m, but between the lowest and the highest measurements completed, i.e., 0.35 and 1.4 m, which show much less uncertainty.

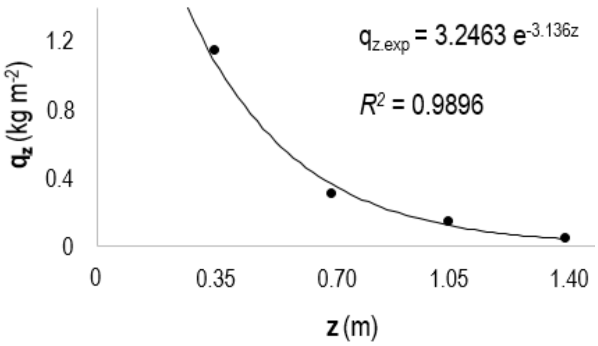


**Figure 5.** Example of estimated sediment fluxes.

As there were two main wind directions (Figures 4 and 6), northeast and south, we compiled a dataset of the differences between data from the masts located upwind and leeward in the main wind directions. The following differences in sediment transport rate were found for NE and S-oriented internal MDt collector compartments on the nine masts. By mast distribution (Figure 7), for sediments from the NE, the averaged differences were Mast 1 less Mast 2; Mast 2 less Mast 4; Mast 3 less Mast 5; Mast 5 less Mast 7; Mast 6 less Mast 8; Mast 8 less Mast 9. For sediments from the S, Mast 9 less Mast 7; Mast 7 less Mast 4; Mast 8 less Mast 5; Mast 5 less Mast 2; Mast 6 less Mast 3; Mast 3 less Mast 1. Table 2 shows the resulting sediment transport rate balance, which clearly indicates particle deposition when coming from the S (positive balance) and particle loss when from the NE (negative balance). When we take into account not only recorded values in the windward compartments but the TOTAL amount corresponding to the whole collector and related to the main wind direction (NE), the resulting balance denotes the general loss of material. Finally, Table 3 shows the results for the total mass transport.

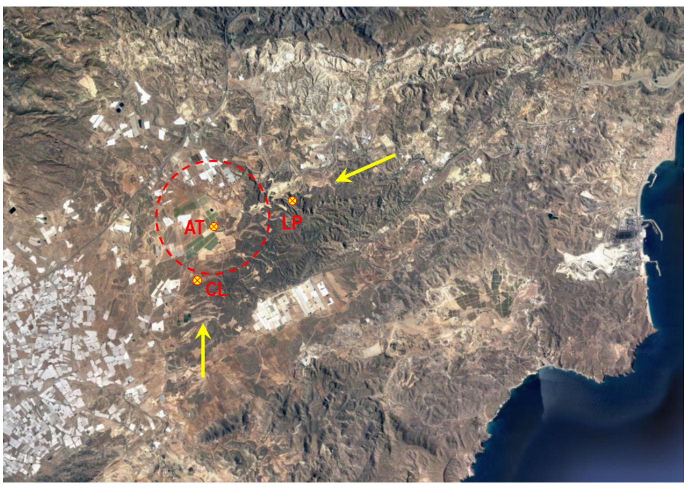


**Figure 6.** Locations of soil types and main wind directions.

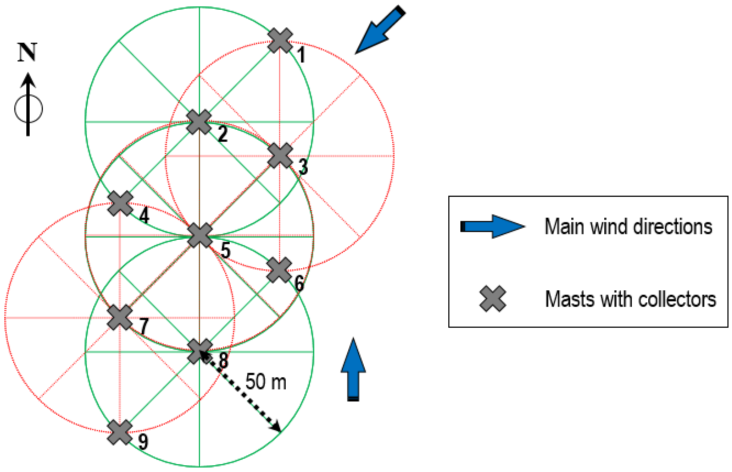


**Figure 7.** Field mast distribution and main wind directions.

**Table 2.** Sediment transport rate ($Q_r$) balance.

| **Sample** | **$Q_r$ Balance** |
|---|---|
| From NE | −0.0103 |
| From S | 0.0079 |
| TOTAL | −0.0154 |

**Table 3.** Total mass transport ($Q_t$).

| **Sample** | **$Q_t$ (kg)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **Average** |
| From NE | 5.2630 | 5.6465 | 5.2825 | 6.1257 | 6.4422 | 5.7794 | 7.0211 | 6.5873 | 7.2174 | 6.1517 |
| From S | 3.0560 | 3.3691 | 3.1766 | 3.5059 | 3.8438 | 3.4755 | 4.0768 | 3.7701 | 4.1908 | 3.6072 |
| TOTAL | 16.9775 | 18.8218 | 17.8462 | 19.2632 | 21.4739 | 19.5251 | 22.6488 | 20.7148 | 23.2820 | 20.0615 |

The soils surrounding the Anthrosols are quite different. Therefore, we tested the mineralogy of the Anthrosols in front of the mast receiving sediments from the NE and S. Due to the small amount of sediment trapped for analysis, we mixed sediments from the nine masts at the same height and direction of origin in order to have enough material.

Along with organic matter, various colloidal minerals condition cation-exchange capacity in soils. Thus, loss of these components from wind erosion leads to a lower soil cation-exchange capacity, which requires them to be added as fertilizer to avoid loss of soil productivity [23,24]. It is therefore important to know what and how much of each soil mineral type is lost. When XRD was applied to our samples, a strong difference in the nature of constituents was observed, as shown in both the diffractograms (Figure 8) and in Table 4. Obtained values with the EVA program from the Diffract Evaluation 2.1 software package, although semi-quantitative, allow obtaining a general idea. Mineralogical relationships between Anthrosols and sediments coming through may have been influenced by deposits generated by continuous wind, mainly from the northeast (Figures 5 and 7).

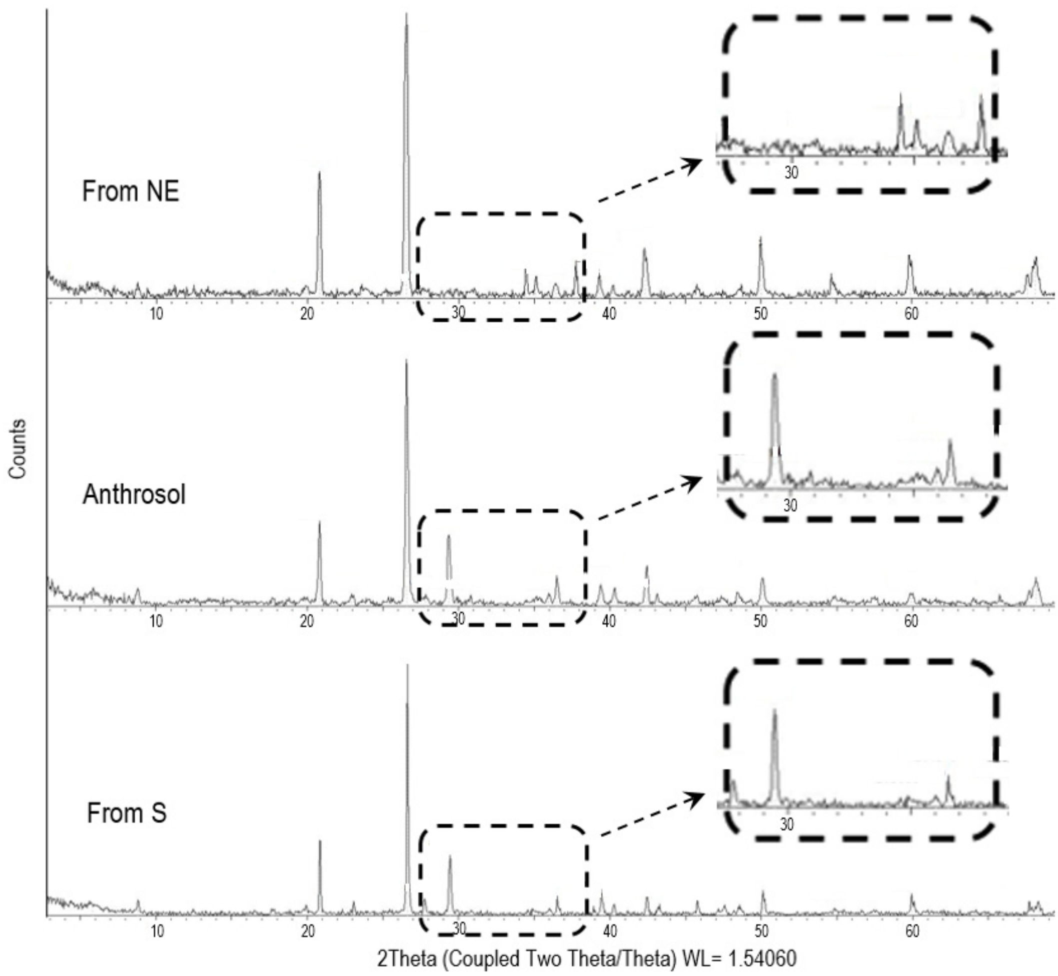


**Figure 8.** Comparative X-ray diffractograms of Anthrosols and sediments in MDt compartments.

**Table 4.** Mineralogical components for Anthrosols and sediments in MDt compartments.

| Sample | Smectite/ Vermiculite (%) | Illite (%) | Kaolinite (%) | Calcite (%) | Dolomite (%) | Quartz (%) | Feldspar (%) | Others (%) |
|---|---|---|---|---|---|---|---|---|
| $AT_h$ | 13 | 18 | 12 | 16 | 3 | 27 | 6 | 5 |
| NE-35 | 11 | 13 | 15 | 5 | 2 | 47 | 5 | 2 |
| NE-70 | 12 | 12 | 18 | 3 | 1 | 45 | 7 | 2 |
| NE-105 | 16 | 14 | 17 | 2 | 1 | 39 | 10 | 1 |
| NE-140 | 16 | 18 | 19 | 1 | 0 | 34 | 12 | 0 |
| S-35 | 21 | 14 | 7 | 26 | 5 | 17 | 6 | 4 |
| S-70 | 24 | 19 | 7 | 23 | 3 | 15 | 5 | 4 |
| S-105 | 27 | 27 | 9 | 14 | 2 | 16 | 4 | 1 |
| S-140 | 30 | 28 | 10 | 11 | 1 | 15 | 4 | 1 |

Note: Sediment trap data labels include direction of origin and catchment height in cm.

## 4. Discussion

Freshly plowed Anthrosols produce high emission flux due to partial breakdown of crust and clods, generating a high proportion of non-cohesive substrate, which increases the amount of wind-blown erodible material. As the organic matter content in these finely tilled soils is very low, mechanical reduction of aggregate sizes decreases aggregate stability, particularly under the dry soil conditions [25], increasing wind-erodible material on the soil surface, including nutrients [26]. This situation is aggravated due to the usually long droughts in the area. On the other hand, a physical crust develops within 9–11 days after tillage, decreasing loose soil wind-erodible materials [7].

Analysis of transport rates and balance of sediments from the south indicated that material was being deposited rather than lost. The lower total mass transport of sediments from the south is influenced by their constituents. A large amount of phyllosilicates was captured in the upper traps, which involves stronger sediment adhesiveness, and therefore, increases aggregation while decreasing their erodibility. Moreover, sediments coming from the south are rich in calcium carbonate, mainly calcite, which is a powerful aggregate, also decreasing their wind erodibility.

The opposite is the case of sediments coming from the northeast, with almost double the total mass transport. The higher amount in captured quartz, much more in lower traps, subserves abrasion processes that increase soil erodibility. Nevertheless, higher values of organic matter found in sediments from the NE bring on some aggregation which balances the material loss process.

The balance of loss and gain in organic matter and clay influences soil productivity, mainly responsible for cation-exchange capacity. In the end, the Anthrosols studied were affected by different inputs, depending on the dominant wind direction, either enriched with calcium carbonate by strong south winds or undergoing quartz movement by strong northeast winds.

Due to the total mass transport values found, further studies must be completed to evaluate, for example, the use of windbreaks to reduce soil wind erosion. Asensio et al. [27] used removable windbreaks following tillage, which reduced erosion until surface crusts formed, and also retained sediments transported by wind. They installed mesh with a $13 \times 30/cm^{-2}$ thread count and 39% porosity, arranged perpendicular to the main natural wind direction, in alternating bands spaced 40 m apart, which reduced erosion by an average up to 72% at a height of 0.4 m in recently tilled olive groves. Due to their easy installation and dismantling, such plastic meshes can be widely employed in windy areas where they are not required permanently. However, that will be the object of further research.

## 5. Conclusions

The MDt collector is a wind-transported particle collector of our own design, is very efficient, and easily and economically manufactured. Inner compartments allow the main wind direction and its intensity to be found from their windward deposits. The results showed that wind-borne materials differed widely, depending on the main wind direction and height of blown material. In the case of the study of these Anthrosols from southeastern Spain, both calcium carbonate from Calcisols located to the south and quartz from Leptosols located to the northeast were transported close to the ground, while clay minerals were transported higher, so they moved further away. X-ray diffractograms of the sediments captured from the two main wind directions show a great disparity of components. The final balance on Anthrosols characteristics will depend on the intensity of loss or deposit of materials from windward surrounding Calcisols and Leptosols that act as a source of sediments due to the wind effect. The movement of material was qualitative and quantitative, requiring preventive measures to minimize soil degradation.

**Author Contributions:** Conceptualized, conceived and designed the experiments: R.G. and C.A.; Performed the experiments and formal analysis: R.G., A.I.M. and C.A.; Writing, original draft preparation: R.G., C.A. and J.L.V.; Writing, review and editing: C.A.; Supervision, grant management and funding acquisition, C.A. All authors have read and agreed to the published version of the manuscript.

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# CONCLUSIONES Y TRABAJOS FUTUROS

# 6. CONCLUSIONES Y TRABAJOS FUTUROS

**1**. Un túnel de viento es un dispositivo cerrado en el que no hay entrada de depósitos de barlovento. Se utiliza principalmente para evaluar la erosionabilidad eólica del suelo, más que la erosión global, aunque los resultados obtenidos mantienen una correlación muy estrecha con los datos de los colectores de partículas.

**2**. El túnel proporciona resultados mucho más rápidos. Sin embargo, con los colectores, se puede determinar la pérdida general o la deposición de partículas, y esto no es detectable a mayor escala utilizando sólo el túnel de viento.

**3**. Los nuevos colectores multidireccionales MDt, de diseño propio, son muy económicos, fabricándose fácilmente con una impresora 3D industrial, a partir de filamentos termoplásticos de politereftalato de etileno modificado con glicol. Presentan una estructura toroidal inferior que alberga ocho cápsulas (o contenedores) orientadas respecto a la dirección norte-sur.

**4**. En nuestros estudios confirmamos la mayor eficiencia de los nuevos colectores MDt, frente a los clásicos colectores BSNE de Fryrear.

**5**. Los mástiles que portan los colectores se distribuyen creando una red y manteniendo 50 m de distancia entre sí. Se trata de dispositivos únicos para evaluar las partículas transportadas por el viento capturadas, en relación con su dirección de origen. Sin embargo, requieren un tiempo de evaluación más largo que el túnel de viento. Por ello, la elección de uno u otro método depende de la precisión, la financiación y el tiempo de ejecución requerido para cada experimento.

**6**. Cuando comparamos los resultados obtenidos al utilizar los colectores MDt en Anthrosoles, Leptosoles, Arenosoles, Cambisoles, Calcisoles, Fluvisoles o Luvisoles almerienses, observamos diferencias condicionadas por la intensidad del labrado en Anthrosoles frente a Leptosoles de parajes naturales, o la influencia del efecto protector de la vegetación de Arenosoles costeros frente a los efectos de la formación de costras físicas en Cambisoles cultivados con olivos. También se observa el incremento de intensidad de los procesos eólicos al enfrentar Calcisoles frente a Fluvisoles con un cultivo de naranjos y Luvisoles con olivos. En el caso de suelos cultivados, tiene gran influencia los días que hacen desde la última labor, por la tendencia al encostramiento en nuestra zona.

**7**. Además, los resultados muestran que los materiales transportados por el viento difieren ampliamente, dependiendo de la dirección principal del viento. En el caso del estudio de Antrosoles del sureste español, tanto el carbonato cálcico de los Calcisoles ubicados al sur de los mismos, como el cuarzo de los Leptosoles ubicados a su noreste, fueron transportados a poca altura del suelo, mientras que los minerales arcillosos se transportaron a más altura, por lo que los depósitos se produjeron a mayor distancia. Los difractogramas de rayos X de los sedimentos capturados de las dos direcciones principales del viento muestran una gran disparidad de componentes. El balance final en las características de los Antrosoles dependerá de la intensidad de la pérdida o depósito de materiales de los Calcisoles y Leptosoles circundantes a barlovento, que actúan como fuente de sedimentos por efecto del viento. Este movimiento cualitativo y cuantitativo de material, implica el requerimiento de medidas preventivas para minimizar la degradación del suelo.

**8**. Como probablemente la captación de partículas a muy poca altura sea el principal inconveniente de los colectores, estamos ensayando nuevos dispositivos que permitan atrapar las que siguen mecanismos de saltación muy próximos a la superficie y, sobretodo, las desplazadas por reptación. Se trata de modificar la distribución y el sistema de anclaje de los colectores en los mástiles. Como ejemplo, podemos ver la figura 29, donde partimos de enterrar una base estable y utilizamos un aro metálico que sirva de apoyo de la apertura del primer colector, a ras de superficie.

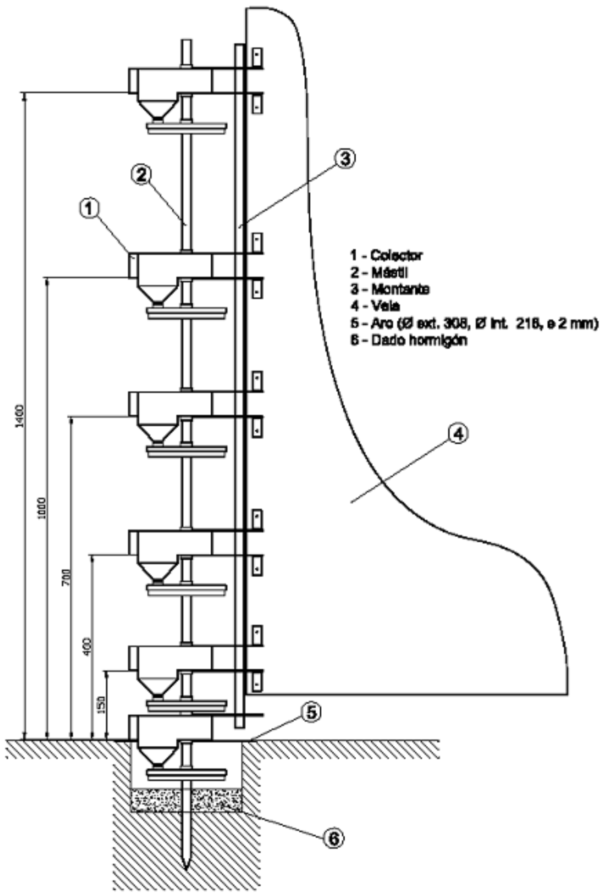


***Figura 29.*** *Disposición de colectores MDt desde la superficie.*

**9**. Creemos que el dispositivo ensayado, los nuevos colectores MDt, muestra un buen potencial, aunque se requieren más pruebas en experimentos futuros, actualmente en fase de desarrollo, que incluirán la incorporación de sensores y microcontroladores para monitorizar en tiempo real la erosión eólica.

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# INDICIOS DE CALIDAD DE LOS ARTÍCULOS

# 8. INDICIOS DE CALIDAD DE LOS ARTÍCULOS

MULTIDIRECTIONAL TRAPS AS A NEW ASSESSMENT SYSTEM OF SOIL WIND EROSION. 2021

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SOIL WIND EROSION CHARACTERIZATION IN SOUTH-EASTER SPAIN USING TRADITIONAL METHODS INFRONT OF AN INNOVATIVE TYPE OF DUST COLLECTOR. 2020

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