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Formal *meta*-specific intramolecular Friedel–Crafts allylic alkylation of phenols through a spirocyclization–dienone–phenol rearrangement cascade

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ABSTRACT

Formal *meta*-specific intramolecular Friedel–Crafts allylic alkylation of phenols was achieved based on spirocyclization–dienone–phenol rearrangement cascades. Systematic screening of acid catalysts revealed that $Sc(OTf)_3$ was a highly effective catalyst for dienone–phenol rearrangement of spiro[4.5]cyclohexadienones. Using 5 mol % of $Sc(OTf)_3$ as the promoter, various spirocyclic substrates were transformed into the corresponding phenol derivatives in good to excellent yield. Furthermore, the one-pot sequential spirocyclization–dienone–phenol rearrangement proceeded using a palladium and scandium multi-catalytic system or a triphenylmethyl cation single-catalyst system, providing the corresponding *meta*-allylated phenol derivatives in excellent yield.

1. Introduction

Aromatic ring functionalization through a C–C bond forming reaction is an important process in organic synthesis because such molecular frameworks are widely distributed in natural products, pharmaceuticals, and functional materials. Various synthetic methods have therefore been developed based on the lithiation–alkylation sequence,[1] transition metal-catalyzed cross-coupling reactions,[2] η^6-arene metal complex-mediated reactions,[3] transition metal-mediated C–H bond functionalization,[4] and others. Friedel–Crafts reaction is another useful method for synthesizing functionalized aromatic rings through a nucleophilic aromatic substitution.[5] Both electronic and steric properties of substituents on the aromatic ring generally affect the reactivity, as well as the reaction orientation. When phenols are utilized as aromatic substrates in Friedel–Crafts reaction, nucleophilic aromatic substitution exclusively occurs at the *ortho*- and/or *para*-positions to the hydroxyl group, providing multi-substituted aromatic compounds. On the other hand, direct introduction of substituents at the *meta*-position to the hydroxyl group remains a highly challenging task in modern synthetic organic chemistry.[6]

As part of our ongoing studies aimed at developing novel synthetic method for spirocyclic molecules, we recently reported a Pd-catalyzed intramolecular *ipso*-Friedel–Crafts allylic alkylation of *para*-substituted phenol derivatives, which produced spiro[4.5]cyclohexadienones in excellent yield [Scheme 1(a)].[7] Moreover, the spirocyclization could be extended to a Pd-catalyzed sequential process: Heck insertion to an allene–*ipso*-Friedel–Crafts allylic alkylation cascade [Scheme 1(b)].[7d] 3,3-Disubstituted cyclohexadienones undergo dienone–phenol rearrangement in the presence of an acid catalyst to give the corresponding 3,4-disubstituted phenol derivatives.[8] We hypothesized that the Pd-catalyzed spirocyclization and an acid-catalyzed dienone–phenol rearrangement sequence would lead to a formal *meta*-specific intramolecular Friedel–Crafts allylic alkylation of phenols. Furthermore, if these two reactions could be performed in a single pot without interfering with the individual catalytic processes, the synthetic efficiency could be significantly increased in terms of pot economy.[9] Herein we report two sets of formal *meta*-specific intramolecular Friedel–Crafts allylic alkylations of phenols through a spirocyclization–dienone–phenol rearrangement cascade.

2. Results and discussions

Our investigation began with spiro[4.5]cyclohexadienone **1a**, which was prepared using the Pd-catalyzed intramolecular *ipso*-Friedel–Crafts allylic alkylation of phenols (Table 1). We first examined the reaction using 5 mol % of $TsOH\cdot H_2O$, the most conventional Brønsted acid promoter for dienone–phenol

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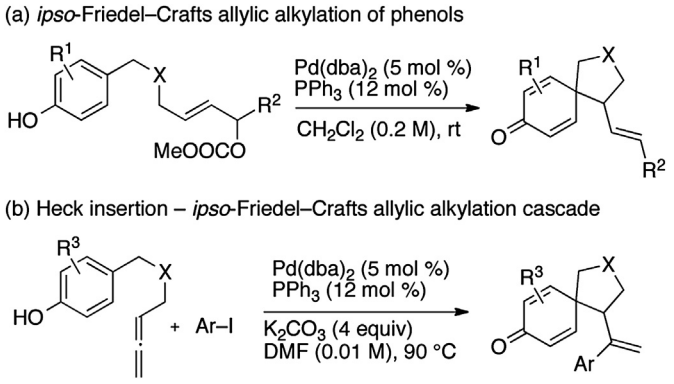
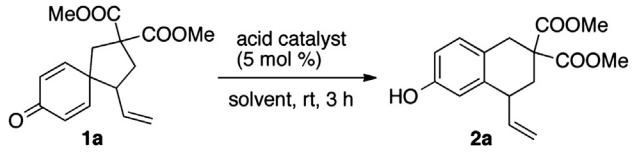


Scheme 1. Pd-catalyzed intramolecular *ipso*-Friedel–Crafts allylic alkylation of phenols.

Table 1
Screening of the acid catalyst



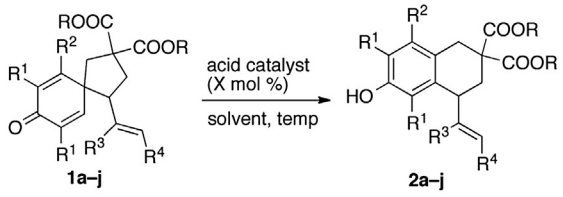
Entry	Acid catalyst	Solvent	Yield (%)[a]
1	$TsOH\cdot H_2O$	CH_3CN	91
2	$BF_3\cdot OEt_2$	CH_3CN	92
3	$Mg(OTf)_2$	CH_3CN	No reaction
4	$Zn(OTf)_2$	CH_3CN	9
5	$Cu(OTf)_2$	CH_3CN	84
6	$Sc(OTf)_3$	CH_3CN	91
7	$Yb(OTf)_3$	CH_3CN	90
8	$FeCl_3$	CH_3CN	90
9	$AuCl_3$	CH_3CN	89
10	$Sc(OTf)_3$	CH_3NO_2	91
11	$Sc(OTf)_3$	Toluene	64
12	$Sc(OTf)_3$	CH_2Cl_2	75
13	$Sc(OTf)_3$	THF	38

[a] Isolated yield.

rearrangements. Tetralinol derivative **2a** was obtained in 91% yield as a single regioisomer, indicating selective migration of a branched alkyl group during this transformation (entry 1). Lewis acidic reagents, such as $BF_3\cdot OEt_2$ or BCl_3 are also utilized as promoters in dienone–phenol rearrangements. The reaction proceeded smoothly in the presence of 5 mol % of $BF_3\cdot OEt_2$, giving **2a** in a similar yield with that obtained using $TsOH\cdot H_2O$ (entry 2). Screening of other Lewis acids was performed using 5 mol % of acid catalyst in CH_3CN at room temperature (Entries 3–9). A variety of metal triflates and metal halides functioned as effective catalysts for this transformation. Among the examined Lewis acids, $Sc(OTf)_3$ was selected as the best catalyst in terms of high yield, water/protic solvent compatibility,[10] and easy handling. In addition, the solvent effect was examined using 5 mol % of $Sc(OTf)_3$ (Entries 10–13). Bicyclic product **2a** was obtained in 91% yield when CH_3NO_2 was used as a solvent.

With the optimized reaction conditions in hand, the substrate scope of dienone–phenol rearrangement was explored using $TsOH\cdot H_2O$ as a Brønsted acid catalyst or $Sc(OTf)_3$ as a Lewis acid catalyst (Table 2). In addition to the model substrate **1a** (entry 1), spirocyclohexadienones **1b** and **1c**, bearing dimethyl or dimethoxy groups at the α-positions to the ketone, were converted into the corresponding tetralinols **2b** and **2c** in excellent yield under both catalytic reaction conditions (Entries 2 and 3). The use of substrates with a substituent at the β-position to ketones **1d** and **1e** significantly decreased the reactivity. The $Sc(OTf)_3$ catalyst system was more suitable for this type of substrate and products **2d** and **2e** were obtained in 80% yield and 53% yield, respectively (Entries 4 and 5). More striking differences in the reactivity between the two catalyst conditions were observed when naphthoquinone derivative **2f** was used as a starting material (entry 6). $Sc(OTf)_3$ was also effective when the substrates were spirocyclohexadienones bearing a *trans*-substituted olefin **1g** and **1h** or a *gem*-substituted olefin **1i**. Using 5 mol % of the catalyst, the corresponding products **2g**–**i** were obtained in 77%–93% yield (entry 7–9). On the other hand, the $TsOH\cdot H_2O$ catalyst system afforded much better results when di-*tert*-butylmalonate tethered substrate **1j** was used (entry 10).[11]

Table 2
Scope and Limitation

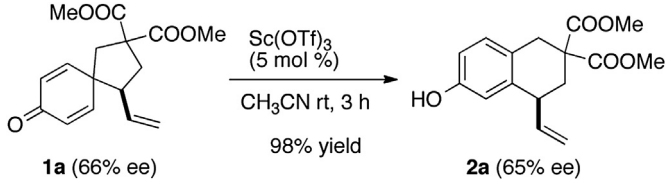


1b, 2b: R = Me, R^1 = Me, R^2 = H, R^3 = H, R^4 = H
1c, 2c: R = Me, R^1 = OMe, R^2 = H, R^3 = H, R^4 = H
1d, 2d: R = Me, R^1 = H, R^2 = Me, R^3 = H, R^4 = H
1e, 2e: R = Me, R^1 = H, R^2 = OMe, R^3 = H, R^4 = H
1f, 2f: R = Me, R^1, R^2 = $CH(CH)_2CH$, R^3 = H, R^4 = H
1g, 2g: R = Me, R^1 = H, R^2 = H, R^3 = H, R^4 = Me
1h, 2h: R = Me, R^1 = H, R^2 = H, R^3 = H, R^4 = Ph
1i, 2i: R = Me, R^1 = H, R^2 = H, R^3 = Ph, R^4 = H
1j, 2j: R = *t*-Bu, R^1 = H, R^2 = H, R^3 = H, R^4 = H

Entry	Substrate	Solvent	Time (h)	Temp (°C)	X (mol %)	Product	Yield (%)[a]	
							Catalyst: $TsOH\cdot H_2O$	Catalyst: $Sc(OTf)_3$
1	**1a**	CH_3CN	3	rt	5	**2a**	91	91
2	**1b**	CH_3CN	3	rt	5	**2b**	98	98
3	**1c**	CH_3CN	3	rt	5	**2c**	91	93
4[b,c]	**1d**	CH_3CN	14	rt	5	**2d**	26	80
5[b,c]	**1e**	CH_3CN	57	Reflux	20	**2e**	31	53
6[b,c]	**1f**	CH_3CN	30	rt	5	**2f**	4	80
7[c]	**1g**	CH_3CN	3	rt	5	**2g**	65	93
8[c]	**1h**	CH_3CN	3	rt	5	**2h**	74	93
9	**1i**	CH_3CN	2	rt	5	**2i**	39	77
10	**1j**	CH_3CN	0.5	rt	5	**2j**	96	17[d]

[a] Isolated yield.
[b] Diastereomeric mixtures were used as substrates. **1d** (dr. 14:1), **1e** (dr. 1.3:1), **1f** (dr. 2.1:1).
[c] Reactions were carried out under diluted conditions (0.02 M) to prevent the formation of side products.
[d] Reaction time: 15 h.

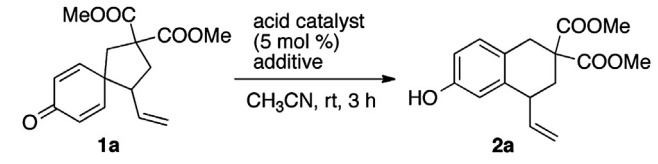
Spirocyclic compounds **1** are available in an optically active form by changing the achiral triphenylphosphine into a chiral phosphorus ligand in the Pd-catalyzed intramolecular *ipso*-Friedel–Crafts allylic alkylation of phenols. When optically active **1a** (66% ee)[12] was treated with the optimized reaction conditions, **2a** was obtained in 98% yield without a significant loss of enantiomeric purity (65% ee). This result clearly demonstrated the applicability of the present cascade process to the asymmetric synthesis (Scheme 2).[13]



Scheme 2. Dienone–phenol rearrangement using an optically active substrate.

The compatibility of the second catalysis with the first reaction conditions is key to the success of the one-pot sequential spirocyclization–dienone–phenol rearrangement using a multi-catalytic reaction system. Therefore, we performed experiments to investigate the influence of the constituents of the first Pd-catalyzed spirocyclization on the second acid catalysis (Table 3).[14] First, a dienone–phenol rearrangement of **1a** was examined using 5 mol % of $TsOH\cdot H_2O$ in the presence of additives. Compared with the control experiments (entry 1), the addition of MeOH (1 equiv) to the reaction did not affect the reactivity (entry 4). In contrast, the addition of 5 mol % of $Pd(dba)_2$ or 12 mol % of PPh_3 retarded the catalytic activities (Entries 2 and 3). The same experiments were also performed using $Sc(OTf)_3$ as the catalyst. Reactions proceeded smoothly in the presence of 5 mol % of $Pd(dba)_2$ or 1 equiv of MeOH (Entries 6 and 8). On the other hand, there was a decreased reactivity when using PPh_3 as the additive probably due to the Lewis basic properties of PPh_3 (entry 7). A prolonged reaction time, however, resulted in gradual consumption of **1a** (entry 7), suggesting that the target one-pot sequential catalysis would proceed by using a slightly larger amount of $Sc(OTf)_3$ than that of PPh_3.

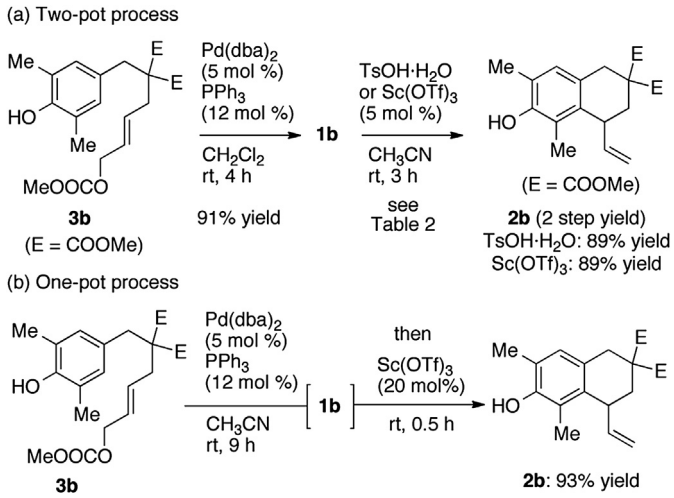
Table 3
Compatibility of the reaction conditions



Entry	Acid catalyst	Additive	Yield (%)[a]
1	$TsOH\cdot H_2O$	—	>99
2	$TsOH\cdot H_2O$	$Pd(dba)_2$ (5 mol %)	9
3	$TsOH\cdot H_2O$	PPh_3 (12 mol %)	14
4	$TsOH\cdot H_2O$	MeOH (1 equiv)	94
5	$Sc(OTf)_3$	—	>99
6	$Sc(OTf)_3$	$Pd(dba)_2$ (5 mol %)	>99
7	$Sc(OTf)_3$	PPh_3 (12 mol %)	50 (78)[b]
8	$Sc(OTf)_3$	MeOH (1 equiv)	97

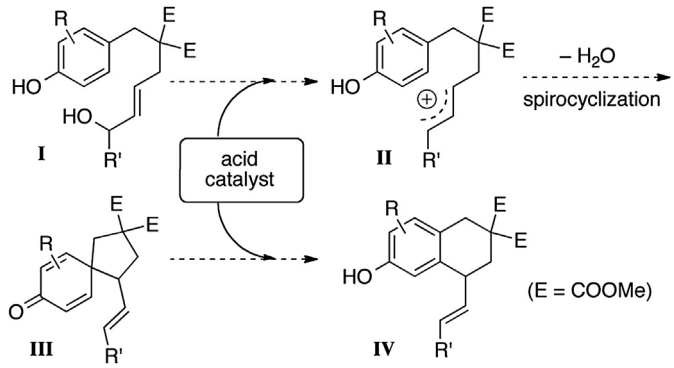
[a] Yields were determined by ^1H NMR analysis of the crude sample.
[b] Reaction time: 12 h.

The promising data in the compatibility studies led us to examine a one-pot sequential multi-catalytic process using **3b** as a substrate. Pd-catalyzed intramolecular *ipso*-Friedel–Crafts allylic alkylation of **3b** proceeded under the optimized reaction conditions, providing **1b** in 91% isolated yield. The obtained product was then treated with 5 mol % of acid catalyst in CH_3CN to give **2b** in 98% yield (See Table 2, entry 2). Consequently, the formal *meta*-specific Friedel–Crafts allylic alkylation of **3b** proceeded in 89% overall yield in a two-pot reaction [Scheme 3(a)]. On the other hand, after completion of the Pd-catalyzed spirocyclization of **3b** in CH_3CN, 20 mol % of $Sc(OTf)_3$ were directly added to the reaction mixture. The second dienone–phenol rearrangement proceeded to completion in 0.5 h and the target compound **2b** was obtained in 93% yield in the one-pot process [Scheme 3(b)].[15]



Scheme 3. One-pot multi-catalytic sequential process.

When both Pd catalyst and $Sc(OTf)_3$ coexisted in the reaction mixture at the initial stage of the reaction, the first Pd-catalyzed spirocyclization did not proceed at all. We thus turned our attention to develop a spirocyclization–dienone–phenol rearrangement cascade process promoted by a single-catalyst. Our reaction design towards this end is outlined in Scheme 4. Treatment of allylic alcohol derivatives **I** with an acid catalyst should lead to the formation of allylic cation intermediates **II**. Subsequent *ipso*-Friedel–Crafts allylic alkylation of phenols would provide spirocyclic molecules **III**.[16] Dienone–phenol rearrangement of **III** should proceed sequentially in the presence of the same acid catalyst, producing formal *meta*-specific Friedel–Crafts reaction product **IV**.

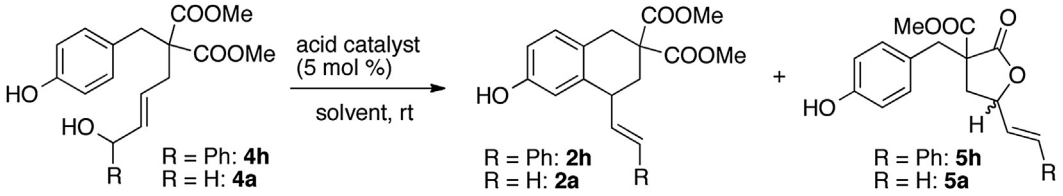


Scheme 4. Plan for the acid-catalyzed cascade reaction.

The reaction conditions were optimized using compound **4h** as a substrate (Table 4). We first examined the reaction using 5 mol % of $Sc(OTf)_3$ in CH_3CN at room temperature. The desired product **2h** was obtained in 60% yield, accompanied by the formation of lactone derivative **5h** as a diastereomeric mixture (31% yield, dr. 7.0:1)

(entry 1).[17] The reaction media significantly affected the reactivity, and the best results were obtained when the reaction was performed in CH_3NO_2 (entry 4). Screening of other Lewis acids revealed that triphenylmethyl perchlorate was the most effective catalyst for this cascade reaction and **2h** was obtained in 85% yield without noticeable formation of **5h** (entry 8). The reaction using 20 mol % of Brønsted acid catalysts gave less satisfactory results (Entries 9 and 10). Furthermore, the reaction using simple allylic alcohol substrate **4a** proceeded under the optimized conditions, providing **2a** in 59% yield (entry 11). This result demonstrated the potential for broad substrate applicability of this catalytic cascade reaction.[18]

Table 4
Optimization of the reaction conditions



Entry	Substrate	Acid catalyst	Solvent	Time (h)	Yield of **2** (%)	Yield of **5** (%) [diastereomeric ratio]
1	**4h**	$Sc(OTf)_3$	CH_3CN	3	60	31 [7.0:1]
2	**4h**	$Sc(OTf)_3$	CH_2Cl_2	3	22	10 [2.6:1]
3	**4h**	$Sc(OTf)_3$	THF	3	4	32 [3.0:1]
4	**4h**	$Sc(OTf)_3$	CH_3NO_2	3	69	12 [1:1.2]
5	**4h**	$Yb(OTf)_3$	CH_3NO_2	3	45	13 [12.3:1]
6	**4h**	$Cu(OTf)_2$	CH_3NO_2	3	54	10 [2.9:1]
7	**4h**	$Zn(OTf)_2$	CH_3NO_2	3	39	7 [4.6:1]
8	**4h**	Ph_3CClO_4	CH_3NO_2	3	85	—
9	**4h**	$TsOH\cdot H_2O$[a]	CH_2Cl_2	24	31	57 [1:1.1]
10	**4h**	TFA[a]	CH_2Cl_2	24	7	15 [2.0:1]
11	**4a**	Ph_3CClO_4	CH_3NO_2	24	59	15 [1.2:1]

[a] 20 mol % of acid catalyst was used.

3. Conclusion

We successfully achieved a formal *meta*-specific intramolecular Friedel–Crafts allylic alkylation of phenols based on a one-pot sequential catalysis. Systematic screening of acid catalysts revealed that $Sc(OTf)_3$ was a highly effective catalyst for dienone–phenol rearrangement of spiro[4.5]cyclohexadienones. The one-pot sequential spirocyclization–dienone–phenol rearrangement proceeded using a palladium and scandium multi-catalytic system or a triphenylmethyl cation single-catalyst system, providing the 3,4-disubstituted phenol derivatives in good to excellent yield.

4. Experimental

4.1. General

Infrared (IR) spectra were recorded on a JASCO FT/IR 230 Fourier transform infrared spectrophotometer, equipped with ATR (Smiths Detection, DuraSample IR II). NMR spectra were recorded on a JEOL ecp 400 spectrometer, operating at 400 MHz for ^1H NMR, and 100 MHz for ^{13}C NMR. Chemical shifts in $CDCl_3$, were reported downfield from TMS (=0 ppm) for ^1H NMR. For ^{13}C NMR, chemical shifts were reported in the scale relative to the solvent signal [$CHCl_3$ (77.0 ppm)] as an internal reference. EI mass spectra were measured on JEOL GCmate. ESI mass spectra were measured on JEOL AccuTOF LC-plus JMS-T100L. The enantiomeric excess (ee) was determined by HPLC analysis. HPLC was performed on JASCO HPLC systems consisting of the following: pump, PU-980; detector, UV-970, measured at 254 nm; column, DAICEL CHIRALPAK AD-H, DAICEL CHIRALCEL OD-H; mobile phase, hexane–2-propanol. Reactions were carried out in dry solvent under argon atmosphere. Other reagents were purified by the usual methods.

4.2. Pd-catalyzed spirocyclization of phenols

Spirocyclic derivatives **1a**–**h**, and **1j** were prepared from the corresponding *para*-substituted phenol derivatives with an allyl carbonate unit according to the typical experimental procedure. Spirocyclic compound **1i** was prepared using the reported method. See our preceding papers for details.[7]

4.2.1. Typical experimental procedure for the Pd-catalyzed intramolecular ipso-Friedel–Crafts allylic alkylation of phenols. Compound **3b** (31.7 mg, 0.080 mmol), $Pd(dba)_2$ (2.3 mg, 4.0 μmol), and PPh_3 (2.5 mg, 9.6 μmol) were dissolved in CH_2Cl_2 (0.40 mL), and the resulting mixture was stirred at room temperature. After 4 h, the reaction was quenched with satd aq NH_4Cl, and the mixture was extracted with AcOEt. The organic layer was washed with brine, dried over Na_2SO_4, and then concentrated in vacuo. The obtained residue was purified by flash column chromatography (SiO_2, hexane–AcOEt=4/1) to give **1b** (23.4 mg, 91% yield) as white solid.

*4.2.2. Dimethyl 8-oxo-4-vinylspiro[4.5]deca-6,9-diene-2,2-dicarboxylate (**1a**).* Colorless oil; IR (ATR) ν 2954, 1728, 1662, 1625, 1435, 1408, 1253, 1200, 1173, 1146, 1093, 1069, 993, 929, 886, 858, 771 cm^{-1}; ^1H NMR ($CDCl_3$): δ 2.45 (d, J=14.4 Hz, 1H), 2.52–2.70 (m, 3H), 2.84 (ddd, J=6.8, 6.8, 13.2 Hz, 1H), 3.79 (s, 3H), 3.80 (s, 3H), 5.00 (d, J=18.4 Hz, 1H), 5.01 (d, J=9.6 Hz, 1H), 5.41 (ddd, J=6.8, 9.6, 18.4 Hz, 1H), 6.26 (dd, J=2.0, 10.0 Hz, 1H), 6.31 (dd, J=2.0, 10.0 Hz, 1H), 6.73 (dd, J=3.2, 10.0 Hz, 1H), 6.86 (dd, J=3.2, 10.0 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 38.4, 43.4, 52.0, 53.2, 53.2, 53.4, 58.4, 117.7, 129.1, 130.0, 133.7, 148.9, 152.9, 172.0, 172.3, 185.8; EI-LRMS m/z 290 (M^+); EI-HRMS Calcd for $C_{16}H_{18}O_5$ (M^+): 290.1154. Found: 290.1149. The enantiomeric excess was determined by chiral HPLC analysis (DAICEL CHIRALCEL OD-H, hexane/2-propanol=90/10, flow rate: 0.5 mL/min, t_R 34.6 min (minor-isomer) and 46.8 min (major-isomer), detection at 254 nm).

*4.2.3. Dimethyl 7,9-dimethyl-8-oxo-4-vinylspiro[4.5]deca-6,9-diene-2,2-dicarboxylate (**1b**).* White solid; mp 73–75 °C; IR (ATR) ν 2953,

1731, 1668, 1635, 1435, 1254, 1199, 1086, 909 cm^{-1}; ^1H NMR ($CDCl_3$): δ 1.88 (d, J=1.6 Hz, 3H), 1.90 (d, J=1.6 Hz, 3H), 2.38 (d, J=14.4 Hz, 1H), 2.50–2.65 (m, 3H), 2.75–2.82 (m, 1H), 3.79 (s, 6H), 4.93–4.97 (m, 2H), 5.38 (ddd, J=6.8, 10.0, 17.2 Hz, 1H), 6.49 (dd, J=1.6, 2.8 Hz, 1H), 6.60 (dd, J=1.6, 2.8 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 16.0, 16.3, 38.5, 43.7, 51.3, 53.1, 53.2, 53.3, 58.4, 117.0, 134.4, 135.0, 136.0, 144.0, 148.4, 172.3, 172.6, 187.2; ESI-LRMS m/z 341 ($M+Na^+$); ESI-HRMS Calcd for $C_{18}H_{22}NaO_5$ ($M+Na^+$): 341.1365. Found: 341.1322.

*4.2.4. Dimethyl 7,9-dimethoxy-8-oxo-4-vinylspiro[4.5]deca-6,9-diene-2,2-dicarboxylate (**1c**).* White solid; mp 119–120 °C; IR (ATR) ν 2954, 1729, 1668, 1617, 1436, 1253, 1200, 1109, 928, 871 cm^{-1}; ^1H NMR ($CDCl_3$): δ 2.40 (d, J=14.4 Hz, 1H), 2.59–2.69 (m, 2H), 2.77 (d, J=14.4 Hz, 1H), 2.81–2.88 (m, 1H), 3.64 (s, 3H), 3.69 (s, 3H), 3.79 (s, 3H), 3.80 (s, 3H), 4.95–5.00 (m, 2H), 5.39 (ddd, J=7.2, 10.0, 17.2 Hz, 1H), 5.68 (d, J=2.0 Hz, 1H), 5.83 (d, J=2.0 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 38.4, 45.7, 50.1, 53.2, 53.2, 54.2, 55.2, 55.3, 58.1, 115.9, 117.4, 120.3, 134.2, 150.8, 151.7, 172.6, 172.6, 176.5; ESI-LRMS m/z 373 ($M+Na^+$); ESI-HRMS Calcd for $C_{18}H_{22}NaO_7$ ($M+Na^+$): 373.1263. Found: 373.1226.

*4.2.5. Dimethyl 6-methyl-8-oxo-4-vinylspiro[4.5]deca-6,9-diene-2,2-dicarboxylate (**1d**).* The titled compound was obtained as an inseparable mixture of diastereomers (white solid). IR (ATR) ν 2954, 1728, 1663, 1626, 1435, 1253, 1200, 1172, 1090, 930, 882, 849, 814 cm^{-1}; ^1H NMR ($CDCl_3$, major diastereomer): δ 2.05 (s, 3H), 2.33 (d, J=15.2 Hz, 1H), 2.62 (d, J=9.6 Hz, 12H), 2.88 (d, J=15.2 Hz, 1H), 3.05 (dt, J=7.2, 9.6 Hz, 1H), 3.79 (s, 3H), 3.81 (s, 3H), 4.97 (dd, J=0.9, 18.0 Hz, 1H), 5.00 (dd, J=0.9, 10.4 Hz, 1H), 5.38 (ddd, J=7.2, 10.4, 18.0 Hz, 1H), 6.24 (dd, J=2.0, 10.4 Hz, 1H), 6.25 (d, J=2.0 Hz, 1H), 6.86 (d, J=10.4 Hz, 1H); ^{13}C NMR ($CDCl_3$, major diastereomer): δ 18.9, 38.4, 42.2, 51.2, 53.2, 53.3, 54.6, 58.3, 117.5, 128.2, 130.5, 133.9, 150.1, 159.2, 172.1, 172.6, 185.7; EI-LRMS m/z 304 (M^+); EI-HRMS Calcd for $C_{17}H_{20}O_5$ (M^+): 304.1311. Found: 304.1304.

*4.2.6. Dimethyl 6-methoxy-8-oxo-4-vinylspiro[4.5]deca-6,9-diene-2,2-dicarboxylate (**1e**).* The titled compound was obtained as an inseparable mixture of diastereomers (colorless oil). IR (ATR) ν 2954, 1732, 1658, 1592, 1436, 1375, 1337, 1256, 1219, 1104, 994, 855 cm^{-1}; ^1H NMR ($CDCl_3$, major diastereomer): δ 2.37–2.44 (m, 1H), 2.49 (d, J=14.0 Hz, 1H), 2.67–2.96 (m, 2H), 3.26 (ddd, J=7.2, 7.2, 14.0 Hz, 1H), 3.75 (s, 3H), 3.78 (s, 3H), 3.80 (s, 3H), 4.93–5.01 (m, 2H), 5.34–5.46 (m, 1H), 5.67 (d, J=1.6 Hz, 1H), 6.14–6.20 (m, 1H), 6.65 (d, J=10.0 Hz, 1H); ^{13}C NMR ($CDCl_3$, major diastereomer): δ 38.2, 42.6, 52.1, 53.1, 53.2, 53.5, 55.8, 58.3, 104.2, 117.5, 127.8, 134.1, 145.4, 172.1, 172.3, 174.6, 187.5; ESI-LRMS m/z 343 ($M+Na^+$); ESI-HRMS Calcd for $C_{17}H_{20}NaO_6$ ($M+Na^+$): 343.1158. Found: 343.1125.

*4.2.7. Dimethyl 4′-oxo-2-vinyl-4′H-spiro(cyclopentane-1,1′-naphthalene)-4,4-dicarboxylate (**1f**).* The titled compound was obtained as an inseparable mixture of diastereomers (white solid). IR (ATR) ν 2954, 1729, 1663, 1599, 1435, 1269, 1202, 1172, 1090, 770 cm^{-1}; ^1H NMR ($CDCl_3$, major diastereomer): δ 2.54 (dd, J=6.0, 13.2 Hz, 1H), 2.75 (d, J=15.2 Hz, 1H), 2.83 (dd, J=6.0, 13.2 Hz, 1H), 2.89 (d, J=15.2 Hz, 1H), 3.14–3.20 (m, 1H), 3.84 (s, 3H), 3.85 (s, 3H), 4.63–4.85 (m, 3H), 6.40 (d, J=10.0 Hz, 1H), 7.01 (d, J=10.0 Hz, 1H), 7.38–7.43 (m, 2H), 7.57 (ddd, J=1.6, 7.2, 8.0 Hz, 1H), 8.14 (dd, J=1.2, 8.0 Hz, 1H); ^{13}C NMR ($CDCl_3$, major diastereomer): δ 39.3, 45.6, 51.9, 53.1, 53.2, 54.7, 60.2, 117.9, 126.6, 126.7, 127.1, 132.1, 132.3, 133.3, 154.8, 155.0, 171.6, 172.7, 184.8; ESI-LRMS m/z 363 ($M+Na^+$); ESI-HRMS Calcd for $C_{20}H_{20}NaO_5$ ($M+Na^+$): 363.1208. Found: 363.1184.

*4.2.8. (E)-Dimethyl 6-methyl-8-oxo-4-(prop-1-enyl)spiro[4.5]deca-6,9-diene-2,2-dicarboxylate (**1g**).* Yellow oil; IR (ATR) ν 2959, 1732, 1665, 1625, 1436, 1255, 1200, 1095, 966, 859 cm^{-1}; ^1H NMR ($CDCl_3$): δ 1.56–1.58 (m, 3H), 2.42 (d, J=14.8 Hz, 1H), 2.50 (dd, J=14.0, 14.0 Hz, 1H), 2.63 (dd, J=6.8, 14.0 Hz, 1H), 2.65 (d, J=14.8 Hz, 1H), 2.79 (ddd, J=6.8, 6.8, 14.0 Hz, 1H), 3.78 (s, 3H), 3.79 (s, 3H), 5.00–5.06 (m, 1H), 5.42 (dq, J=12.8, 6.4 Hz, 1H), 6.25–6.30 (m, 2H), 6.70 (dd, J=3.2, 9.6 Hz, 1H), 6.86 (dd, J=3.2, 10.4 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 17.7, 39.1, 43.4, 52.2, 52.9, 53.1, 53.2, 58.4, 126.3, 128.8, 129.1, 129.9, 149.3, 153.4, 172.1, 172.4, 186.1; EI-LRMS m/z 304 (M^+); EI-HRMS Calcd for $C_{17}H_{20}O_5$ (M^+): 304.1311. Found: 304.1304.

*4.2.9. (E)-Dimethyl 6-methyl-8-oxo-4-styrylspiro[4.5]deca-6,9-diene-2,2-dicarboxylate (**1h**).* Colorless solid; IR (ATR) ν 2958, 1729, 1662, 1625, 1435, 1252, 1199, 1172, 1092, 964, 858, 751, 693 cm^{-1}; ^1H NMR ($CDCl_3$): δ 2.48 (d, J=14.4 Hz, 1H), 2.63–2.78 (m, 3H), 2.99–3.06 (m, 1H), 3.80 (s, 3H), 3.81 (s, 3H), 5.78 (dd, J=7.6, 16.0 Hz, 1H), 6.27–6.37 (m, 3H), 6.79 (dd, J=2.8, 10.0 Hz, 1H), 6.94 (dd, J=2.8, 10.0 Hz, 1H), 7.18–7.28 (m, 5H); ^{13}C NMR ($CDCl_3$): δ 39.0, 43.6, 52.4, 52.9, 53.2, 53.3, 58.5, 125.1, 126.2 (2C), 127.7, 128.5 (2C), 129.3, 130.2, 132.7, 136.2, 149.0, 172.0, 172.3, 185.8; EI-LRMS m/z 366 (M^+); EI-HRMS Calcd for $C_{22}H_{22}O_5$ (M^+): 366.1467. Found: 366.1471.

*4.2.10. Dimethyl 8-oxo-4-(1-phenylvinyl)spiro[4.5]deca-6,9-diene-2,2-dicarboxylate (**1i**).* Colorless oil; IR (ATR): ν 1729, 1662, 1252, 1200, 856, 733, 701 cm^{-1}; ^1H NMR ($CDCl_3$): δ 2.35 (d, J=14.8 Hz, 1H), 2.70 (d, J=14.8 Hz, 1H), 2.76 (dd, J=6.4, 14.0 Hz, 1H), 2.90 (dd, J=13.2, 14.0 Hz, 1H), 3.47 (dd, J=6.0, 13.2 Hz, 1H), 3.79 (s, 3H), 3.83 (s, 3H), 5.10 (s, 1H), 5.11 (s, 1H), 5.59 (dd, J=2.0, 10.0 Hz, 1H), 6.14 (dd, J=2.0, 10.0 Hz, 1H), 6.44 (dd, J=3.2, 10.0 Hz, 1H), 6.83 (dd, J=3.2, 10.0 Hz, 1H), 7.02–7.05 (m, 2H), 7.17–7.20 (m, 3H); ^{13}C NMR ($CDCl_3$): δ 37.5, 44.1, 50.5, 52.9, 53.2, 53.3, 57.5, 114.0, 126.9 (2C), 127.7, 127.7, 128.0 (2C), 128.5, 141.7, 146.5, 149.3, 153.2, 171.9, 172.4, 185.6; ESI-LRMS m/z 389 ($M+Na^+$); ESI-HRMS Calcd for $C_{22}H_{22}NaO_5$ ($M+Na^+$): 389.1359. Found: 389.1385.

*4.2.11. Di-tert-butyl 8-oxo-4-vinylspiro[4.5]deca-6,9-diene-2,2-dicarboxylate (**1j**).* White solid; mp 63–66 °C; IR (ATR) ν 2978, 2933, 1720, 1666, 1627, 1457, 1393, 1368, 1281, 1256, 1211, 1166, 1139, 1094, 922, 857, 738 cm^{-1}; ^1H NMR ($CDCl_3$): δ 1.47 (s, 9H), 1.48 (s, 9H), 2.31 (d, J=14.4 Hz, 1H), 2.46–2.56 (m, 2H), 2.60 (d, J=14.4 Hz, 1H), 2.82 (ddd, J=7.6, 7.6, 15.2 Hz, 1H), 4.97–5.01 (m, 2H), 5.42 (ddd, J=7.6, 10.0, 17.6 Hz, 1H), 6.26 (dd, J=2.0, 10.0 Hz, 1H), 6.30 (dd, J=2.0, 10.0 Hz, 1H), 6.74 (dd, J=3.2, 10.0 Hz, 1H), 6.88 (dd, J=3.2, 10.0 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 27.8 (3C), 27.8 (3C), 38.2, 43.6, 52.2, 53.5, 60.0, 82.0, 82.0, 117.4, 129.1, 129.9, 134.3, 149.5, 153.5, 170.9, 171.2, 186.1; ESI-LRMS m/z 397 ($M+Na^+$); ESI-HRMS Calcd for $C_{22}H_{30}NaO_5$ ($M+Na^+$): 397.1991. Found: 397.1979.

4.3. Acid-catalyzed dienone–phenol rearrangement of spiro[4.5]cyclohexadienones

4.3.1. Typical experimental procedure for Sc(OTf)$_3$-catalyzed dienone–phenol rearrangement of spiro[4.5]cyclohexadienone. **1b** (27.8 mg, 0.087 mmol), and $Sc(OTf)_3$ (2.1 mg, 4.4 μmol) were dissolved in CH_3CN (0.44 mL), and the resulting mixture was stirred at room temperature. After 3 h, the reaction was quenched with satd aq NH_4Cl, and the mixture was extracted with AcOEt. The organic layer was washed with brine, dried over Na_2SO_4, and then concentrated in vacuo. The obtained residue was purified by flash column chromatography (SiO_2, hexane/Et_2O=2/1) to give **2b** (28.6 mg, 98% yield) as colorless oil.

*4.3.2. Dimethyl 6-hydroxy-4-vinyl-3,4-dihydronaphthalene-2,2(1H)-dicarboxylate (**2a**).* Colorless solid; mp 113–115 °C; IR (ATR) ν 3443, 2954, 1721, 1611, 1500, 1436, 1274, 1226, 1056, 1031, 988, 919, 886, 817 cm^{-1}; ^1H NMR ($CDCl_3$): δ 1.98 (dd, J=11.2, 13.6 Hz, 1H), 2.57 (ddd, J=2.0, 6.0, 13.6 Hz, 1H), 3.09 (d, J=15.6 Hz, 1H), 3.33 (dd, J=2.0, 15.6 Hz, 1H), 3.41–3.48 (m, 1H), 3.69 (s, 3H), 3.74 (s, 3H), 4.96 (s, 1H), 5.15–5.20 (m, 2H), 5.72 (ddd, J=6.8, 10.0, 17.2 Hz, 1H), 6.62 (dd,

J=2.8, 8.0 Hz, 1H), 6.63 (d, J=2.8 Hz, 1H), 6.98 (d, J=8.0 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 34.3, 34.9, 41.4, 52.7, 52.8, 53.6, 114.0, 114.8, 116.7, 125.2, 129.9, 137.5, 140.9, 154.0, 171.3, 172.1; ESI-LRMS m/z 313 ($M+Na^+$); ESI-HRMS Calcd for $C_{16}H_{18}NaO_5$ ($M+Na^+$): 313.1052. Found: 313.1005. The enantiomeric excess was determined by chiral HPLC analysis (DAICEL CHIRALPAK AD-H, hexane/2-propanol=90/10, flow rate: 1.0 mL/min, 35 °C, t_R 10.0 min [minor-isomer] and 16.6 min [major-isomer], detection at 254 nm); $[\alpha]_D^{24}$ +13.0 (c 0.87, $CHCl_3$, 65% ee).

*4.3.3. Dimethyl 6-hydroxy-5,7-dimethyl-4-vinyl-3,4-dihydronaphthalene-2,2(1H)-dicarboxylate (**2b**).* Colorless oil; IR (ATR) ν 3502, 2953, 1727, 1636, 1481, 1435, 1249, 1208, 1078, 1053, 921 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 2.06 (s, 3H), 2.20 (s, 3H), 2.33 (ddd, J=1.6, 4.4, 14.0 Hz, 1H), 2.54 (ddd, J=1.6, 7.2, 14.0 Hz, 1H), 2.98 (d, J=16.0 Hz, 1H), 3.31 (d, J=16.0 Hz, 1H), 3.65 (s, 3H), 3.66 (s, 3H), 3.77 (ddd, J=4.4, 6.4, 7.2 Hz, 1H), 4.65 (s, 1H), 4.68 (ddd, J=1.6, 1.6, 17.6 Hz, 1H), 4.98 (ddd, J=1.6, 1.6, 10.4 Hz, 1H), 5.73 (ddd, J=6.4, 10.4, 17.6 Hz, 1H), 6.79 (s, 1H); ^{13}C NMR ($CDCl_3$): δ 11.9, 15.8, 34.8, 34.8, 38.5, 52.3, 52.6, 52.6, 114.9, 121.6, 121.9, 125.5, 128.4, 132.7, 140.6, 150.8, 171.9, 172.0; ESI-LRMS m/z 341 ($M+Na^+$); ESI-HRMS Calcd for $C_{18}H_{22}NaO_5$ ($M+Na^+$): 341.1365. Found: 341.1323.

*4.3.4. Dimethyl 6-hydroxy-5,7-dimethoxy-4-vinyl-3,4-dihydronaphthalene-2,2(1H)-dicarboxylate (**2c**).* White solid; mp 94–96 °C; IR (ATR) ν 3460, 2952, 2843, 1730, 1615, 1498, 1448, 1433, 1294, 1245, 1198, 1124, 1095, 1072, 1002, 915, 882, 827 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 2.23 (dd, J=6.4, 14.0 Hz, 1H), 2.51 (ddd, J=1.6, 7.2, 14.0 Hz, 1H), 3.05 (d, J=15.6 Hz, 1H), 3.27 (d, J=15.6 Hz, 1H), 3.66 (s, 3H), 3.68 (s, 3H), 3.79 (s, 3H), 3.83–3.86 (m, 1H), 3.86 (s, 3H), 4.83 (ddd, J=1.6, 1.6, 17.2 Hz, 1H), 4.99 (ddd, J=1.6, 1.6, 10.4 Hz, 1H), 5.41 (s, 1H), 5.82 (ddd, J=6.8, 10.4, 17.2 Hz, 1H), 6.44 (s, 1H); ^{13}C NMR ($CDCl_3$): δ 34.5, 34.8, 35.9, 52.4, 52.6, 53.0, 56.0, 60.2, 106.2, 113.7, 122.3, 124.9, 137.0, 141.7, 145.2, 146.4, 171.6, 171.9; ESI-LRMS m/z 373 ($M+Na^+$); ESI-HRMS Calcd for $C_{18}H_{22}NaO_7$ ($M+Na^+$): 373.1263. Found: 373.1229.

*4.3.5. Dimethyl 6-hydroxy-8-methyl-4-vinyl-3,4-dihydronaphthalene-2,2(1H)-dicarboxylate (**2d**).* Colorless solid; mp 126–129 °C; IR (ATR) ν 3460, 2953, 2925, 2854, 1721, 1612, 1596, 1435, 1243, 1197, 1147, 1084, 1034, 996, 920, 858, 687 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 2.00 (dd, J=11.2, 13.6 Hz, 1H), 2.21 (s, 3H), 2.53 (ddd, J=2.0, 5.6, 13.6 Hz, 1H), 2.84 (d, J=16.4 Hz, 1H), 3.30 (d, J=16.4 Hz, 1H), 3.38 (ddd, J=5.6, 8.8, 11.2 Hz, 1H), 3.70 (s, 3H), 3.76 (s, 3H), 5.11 (s, 1H), 5.14 (d, J=9.6 Hz, 1H), 5.15 (d, J=17.2 Hz, 1H), 5.70 (ddd, J=8.8, 9.6, 17.2 Hz, 1H), 6.50 (s, 2H); ^{13}C NMR ($CDCl_3$): δ 19.8, 31.5, 34.5, 41.6, 52.8, 52.8, 53.5, 112.5, 115.6, 116.5, 123.8, 137.5, 137.8, 141.1, 153.5, 171.6, 172.4; ESI-LRMS m/z 327 ($M+Na^+$); ESI-HRMS Calcd for $C_{17}H_{20}NaO_5$ ($M+Na^+$): 327.1208. Found: 327.1168.

*4.3.6. Dimethyl 6-hydroxy-8-methoxy-4-vinyl-3,4-dihydronaphthalene-2,2(1H)-dicarboxylate (**2e**).* White solid; mp 114–118 °C; IR (ATR) ν 3450, 2954, 1732, 1605, 1435, 1248, 1195, 1148, 1109, 1055, 977, 923, 843 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 1.98 (dd, J=11.2, 13.2 Hz, 1H), 2.51 (ddd, J=2.0, 6.0, 13.2 Hz, 1H), 2.76 (dd, J=1.2, 16.8 Hz, 1H), 3.35 (ddd, J=6.0, 8.8, 11.2 Hz, 1H), 3.46 (dd, J=2.0, 16.8 Hz, 1H), 3.70 (s, 3H), 3.75 (s, 3H), 3.77 (s, 3H), 5.14 (d, J=9.6 Hz, 1H), 5.15 (s, 1H), 5.15 (d, J=18.0 Hz, 1H), 5.68 (ddd, J=8.8, 9.6, 18.0 Hz, 1H), 6.23 (d, J=1.6 Hz, 1H), 6.24 (d, J=1.6 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 28.4, 34.5, 41.3, 52.7, 52.8, 52.9, 55.4, 96.9, 106.4, 114.3, 116.5, 138.0, 141.0, 154.5, 158.1, 171.6, 172.5; ESI-LRMS m/z 343 ($M+Na^+$); ESI-HRMS Calcd for $C_{17}H_{20}NaO_6$ ($M+Na^+$): 343.1158. Found: 343.1128.

*4.3.7. Dimethyl 9-hydroxy-1-vinyl-1,2-dihydrophenanthrene-3,3(4H)-dicarboxylate (**2f**).* White solid; IR (ATR) ν 3446, 2953, 2924, 2853, 1722, 1628, 1600, 1519, 1434, 1394, 1341, 1260, 1228, 1087, 921, 861, 760 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 2.07 (dd, J=11.2, 13.6 Hz, 1H), 2.66 (ddd, J=2.0, 6.0, 13.6 Hz, 1H), 3.32 (dd, J=2.0, 16.4 Hz, 1H), 3.62 (ddd, J=6.0, 8.8, 11.2 Hz, 1H), 3.66 (s, 3H), 3.80 (s, 3H), 3.87 (d, J=16.4 Hz, 1H), 5.18 (s, 1H), 5.19 (dd, J=1.2, 9.6 Hz, 1H), 5.24 (dd, J=1.2, 16.8 Hz, 1H), 5.72 (ddd, J=8.8, 9.6, 16.8 Hz, 1H), 6.65 (s, 1H), 7.48 (ddd, J=0.8, 8.4, 8.4 Hz, 1H), 7.55 (ddd, J=0.8, 8.4, 8.4 Hz, 1H), 7.98 (d, J=8.4 Hz, 1H), 8.16 (dd, J=0.8, 8.4 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 30.9, 34.6, 42.0, 52.8, 52.9, 53.4, 108.9, 116.8, 120.7, 122.1, 123.0, 123.7, 124.8, 126.7, 133.0, 133.5, 141.5, 149.8, 171.4, 172.4; ESI-LRMS m/z 363 ($M+Na^+$); ESI-HRMS Calcd for $C_{20}H_{20}NaO_5$ ($M+Na^+$): 363.1208. Found: 363.1189.

*4.3.8. (E)-Dimethyl 6-hydroxy-4-(prop-1-enyl)-3,4-dihydronaphthalene-2,2(1H)-dicarboxylate (**2g**).* Colorless solid; mp 88–92 °C; IR (ATR) ν 3461, 2954, 1733, 1611, 1500, 1448, 1273, 1227, 1068, 968, 815 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 1.72 (dd, J=1.6, 6.0 Hz, 3H), 1.95 (dd, J=11.2, 13.6 Hz, 1H), 2.53 (ddd, J=2.0, 6.0, 13.6 Hz, 1H), 3.07 (d, J=16.0 Hz, 1H), 3.32 (dd, J=2.0, 16.0 Hz, 1H), 3.37 (ddd, J=6.0, 8.8, 11.2 Hz, 1H), 3.68 (s, 3H), 3.74 (s, 3H), 5.21 (s, 1H), 5.31–5.37 (m, 1H), 5.60 (dq, J=15.2, 6.0 Hz, 1H), 6.59 (dd, J=2.8, 8.4 Hz, 1H), 6.63 (d, J=2.8 Hz, 1H), 6.95 (d, J=8.4 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 17.8, 34.3, 35.4, 40.2, 52.7, 52.8, 53.7, 113.8, 114.8, 125.1, 127.4, 129.8, 133.7, 138.5, 154.0, 171.5, 172.3; ESI-LRMS m/z 327 ($M+Na^+$); ESI-HRMS Calcd for $C_{17}H_{20}NaO_5$ ($M+Na^+$): 327.1208. Found: 327.1169.

*4.3.9. (E)-Dimethyl 6-hydroxy-4-styryl-3,4-dihydronaphthalene-2,2(1H)-dicarboxylate (**2h**).* White solid; mp 130–132 °C; IR (ATR) ν 3444, 3024, 2953, 1720, 1610, 1498, 1446, 1268, 1225, 1073, 967, 817, 738, 694 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 2.06 (dd, J=11.2, 13.6 Hz, 1H), 2.63 (ddd, J=2.0, 6.0, 13.6 Hz, 1H), 3.13 (d, J=16.4 Hz, 1H), 3.36 (dd, J=2.0, 16.4 Hz, 1H), 3.62 (ddd, J=6.0, 8.8, 11.2 Hz, 1H), 3.68 (s, 3H), 3.72 (s, 3H), 4.96 (s, 1H), 6.11 (dd, J=8.8, 15.6 Hz, 1H), 6.51 (d, J=15.6 Hz, 1H), 6.63–6.65 (m, 2H), 7.01 (d, J=8.4 Hz, 1H), 7.23 (t, J=7.2 Hz, 1H), 7.31 (dd, J=7.2, 7.2 Hz, 2H), 7.37 (d, J=7.2 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ 34.2, 35.1, 40.6, 52.8, 52.9, 53.6, 114.1, 115.0, 125.2, 126.2 (2C), 127.4, 128.6 (2C), 130.1, 131.9, 132.4, 137.0, 137.7, 154.1, 171.3, 172.1; ESI-LRMS m/z 389 ($M+Na^+$); ESI-HRMS Calcd for $C_{22}H_{22}NaO_5$ ($M+Na^+$): 389.1365. Found: 389.1327.

*4.3.10. Dimethyl 6-hydroxy-4-(1-phenylvinyl)-3,4-dihydronaphthalene-2,2(1H)-dicarboxylate (**2i**).* Colorless oil; IR (ATR) ν 3446, 3024, 2953, 1720, 1610, 1499, 1435, 1266, 1224, 1078, 1056, 1030, 907, 820, 780, 735, 702 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 2.06 (dd, J=10.8, 13.6 Hz, 1H), 2.62 (ddd, J=2.0, 6.4, 13.6 Hz, 1H), 3.15 (d, J=16.0 Hz, 1H), 3.33 (dd, J=2.0, 16.0 Hz, 1H), 3.66 (s, 3H), 3.69 (s, 3H), 4.11 (dd, J=6.4, 10.8 Hz, 1H), 4.89 (s, 1H), 5.09 (s, 1H), 5.45 (s, 1H), 6.65 (dd, J=2.4, 8.4 Hz, 1H), 6.74 (d, J=2.4 Hz, 1H), 7.01 (d, J=8.4 Hz, 1H), 7.22–7.27 (m, 5H); ^{13}C NMR ($CDCl_3$): δ 34.4, 34.6, 43.4, 52.7, 52.8, 54.0, 114.1, 114.9, 116.5, 125.8, 126.8 (2C), 127.5, 128.3 (2C), 130.1, 138.2, 140.6, 151.2, 154.2, 171.3, 172.0; ESI-LRMS m/z 389 ($M+Na^+$); ESI-HRMS Calcd for $C_{22}H_{22}NaO_5$ ($M+Na^+$): 389.1365. Found: 389.1345.

*4.3.11. Di-tert-butyl 6-hydroxy-4-vinyl-3,4-dihydronaphthalene-2,2(1H)-dicarboxylate (**2j**).* White solid; mp 152–154 °C; IR (ATR) ν 3448, 2977, 2932, 1712, 1611, 1500, 1455, 1393, 1368, 1278, 1234, 1150, 1053, 915, 846 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 1.37 (s, 9H), 1.46 (s, 9H), 1.88 (dd, J=11.6, 13.6 Hz, 1H), 2.45 (ddd, J=2.0, 6.4, 13.6 Hz, 1H), 2.94 (d, J=16.0 Hz, 1H), 3.23 (dd, J=2.0, 16.0 Hz, 1H), 3.42 (ddd, J=6.4, 8.8, 11.6 Hz, 1H), 4.97 (s, 1H), 5.15 (dd, J=2.0, 10.0 Hz, 1H), 5.17 (dd, J=2.0, 16.8 Hz, 1H), 5.74 (ddd, J=8.8, 10.0, 16.8 Hz, 1H), 6.60 (dd, J=2.4, 8.0 Hz, 1H), 6.62 (d, J=2.4 Hz, 1H), 6.97 (d, J=8.0 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 27.7 (3C), 27.8 (3C), 34.4, 35.0, 41.8, 54.8, 81.2, 81.6, 113.8, 114.6, 116.3, 125.9, 129.8, 138.0, 141.3, 153.9, 170.1, 171.1;

ESI-LRMS m/z 397 ($M+Na^+$); ESI-HRMS Calcd for $C_{22}H_{30}NaO_5$ ($M+Na^+$): 397.1991. Found: 397.1986.

4.4. Spirocyclization–dienone–phenol rearrangement cascade

4.4.1. Experimental procedure for the one-pot sequential multi-catalytic process. Compound **3b** (31.5 mg, 0.080 mmol), $Pd(dba)_2$ (2.3 mg, 4.0 μmol), and PPh_3 (2.5 mg, 9.6 μmol) were dissolved in CH_3CN (0.40 mL), and the resulting mixture was stirred at room temperature. After 9 h, $Sc(OTf)_3$ (7.9 mg, 0.016 mmol) was added, and the reaction was stirred for another 30 min. The reaction was quenched with satd aq NH_4Cl, and the mixture was extracted with AcOEt. The organic layer was washed with brine, dried over Na_2SO_4, and then concentrated in vacuo. The obtained residue was purified by flash column chromatography (SiO_2, hexane/Et_2O=2/1) to give **2b** (24.1 mg, 93% yield) as colorless oil.

4.4.2. Typical experimental procedure for the sequential reaction with a single-catalyst. Compound **4h** (30.7 mg, 0.080 mmol), and Ph_3CClO_4 (1.4 mg, 4.0 μmol) were dissolved in CH_3NO_2 (0.40 mL), and the resulting mixture was stirred at room temperature. After 3 h, the reaction was quenched with water, and the mixture was extracted with AcOEt. The organic layer was washed with brine, dried over Na_2SO_4, and then concentrated in vacuo. The obtained residue was purified by flash column chromatography (SiO_2, hexane/AcOEt=3/1) to give **2h** (24.8 mg, 85% yield) as colorless oil.

*4.4.3. Dimethyl 2-(4-hydroxybenzyl)-2-(4-hydroxybut-2-en-1-yl) malonate (**4a**).* Colorless oil; IR (ATR) ν 3443, 3024, 2952, 1720, 1614, 1516, 1438, 1201, 1174, 1110, 1049, 975, 841 cm^{-1}; ^1H NMR ($CDCl_3$): δ 2.55 (d, J=7.2 Hz, 2H), 3.16 (s, 2H), 3.71 (s, 3H), 3.72 (s, 3H), 4.12 (d, J=5.6 Hz, 2H), 5.63 (dt, J=15.6, 7.2 Hz, 1H), 5.75 (dt, J=15.6, 5.6 Hz, 1H), 6.71 (d, J=8.0 Hz, 2H), 6.93 (d, J=8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ 34.9, 37.4, 52.4 (2C), 59.3, 63.3, 115.3 (2C), 126.2, 127.4, 131.0 (2C), 133.8, 154.9, 171.4 (2C); ESI-LRMS m/z 331 ($M+Na^+$); ESI-HRMS Calcd for $C_{16}H_{20}NaO_6$ ($M+Na^+$): 331.1158. Found: 331.1140.

*4.4.4. (E)-Dimethyl 2-(4-hydroxy-4-phenylbut-2-en-1-yl)-2-(4-hydroxybenzyl)malonate (**4h**).* White solid; mp 101–103 °C; IR (ATR) ν 3443, 3033, 2952, 1719, 1614, 1515, 1437, 1200, 1173, 1109, 1047, 971, 840, 735, 700 cm^{-1}; ^1H NMR ($CDCl_3$): δ 2.36 (s, 1H), 2.52–2.54 (m, 2H), 3.15 (s, 2H), 3.62 (s, 3H), 3.63 (s, 3H), 5.17 (s, 1H), 5.72–5.75 (m, 3H), 6.65 (d, J=8.0 Hz, 2H), 6.87 (d, J=8.0 Hz, 2H), 7.24–7.35 (m, 5H); ^{13}C NMR ($CDCl_3$): δ 34.9, 37.6, 52.4 (2C), 59.3, 74.8, 115.2 (2C), 125.3, 126.1 (2C), 127.3, 127.7, 128.5 (2C), 131.0 (2C), 137.1, 142.6, 154.9, 171.3, 171.4; ESI-LRMS m/z 407 ($M+Na^+$); ESI-HRMS Calcd for $C_{22}H_{24}NaO_6$ ($M+Na^+$): 407.1471. Found: 407.1484.

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Supplementary data

Supplementary data (^1H and ^{13}C NMR charts of the reported compounds) can be found. Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2013.09.042.

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11. When $Sc(OTf)_3$ was used as a Lewis acid catalyst, decarboxylative removal of one of the *tert*-butyl esters occurred, resulting in low isolated yield. Product **2j** was obtained in 76% yield using $AuCl_3$ as a Lewis acid catalyst.
12. Optically active **1a** (66% ee) was prepared from the corresponding linear starting material using 3 mol % of $Pd(dba)_2$ and 3.6 mol % of (*R*,*R*)-ANDENphenyl-Trost ligand in CH_3CN at room temperature (24 h, 58% yield).
13. Compound **1a** can be synthesized in high yield with excellent enantiomeric excess (97% ee) using the chiral Ir catalyst system developed by You, et al. See: Wu, Q.-F.; Liu, W.-B.; Zhuo, C.-X.; Rong, Z.-Q.; Ye, K.-Y.; You, S.-L. *Angew. Chem., Int. Ed.* **2011**, *50*, 4455–4458.
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18. Compound **1a** was smoothly transformed into **2a** in 86% yield by treating with Ph_3CClO_4 in CH_3NO_2. This result reasonably supports our mechanistic hypothesis shown in Scheme 4. On the other hand, spirocyclic intermediates **1a** and **1h** could not be detected in these examinations (monitored by TLC). This would be due to rapid consumption of the spirocyclic intermediates under the cascade reaction conditions.